

A method for unbounded verification of privacy-type properties

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Abstract. In this paper, we consider the problem of verifying anonymity and unlinkability in the symbolic model, where protocols are represented as processes in a variant of the applied pi calculus, notably used in the **ProVerif** tool. Existing tools and techniques do not allow to verify directly these properties, expressed as behavioral equivalences. We propose a different approach: we design two conditions on protocols which are sufficient to ensure anonymity and unlinkability, and which can then be effectively checked automatically using **ProVerif**. Our two conditions correspond to two broad classes of attacks on unlinkability, *i.e.* data and control-flow leaks. This theoretical result is general enough that it applies to a wide class of protocols based on a variety of cryptographic primitives. In particular, using our tool, **UKano**, we provide the first formal security proofs of protocols such as BAC and PACE (e-passport), Hash-Lock (RFID authentication), etc. Our work has also led to the discovery of new attacks, including one on the LAK protocol (RFID authentication) which was previously claimed to be unlinkable (in a weak sense).

Keywords: formal verification, security protocols, symbolic model, equivalence-based properties

1. Introduction

Security protocols aim at securing communications over various types of insecure networks (*e.g.* web, wireless devices) where dishonest users may listen to communications and interfere with them. A *secure communication* has a different meaning depending on the underlying application. It ranges from the confidentiality of data (medical files, secret keys, etc.) to, *e.g.* verifiability in electronic voting systems. Another example of a security notion is privacy. In this paper, we focus on two privacy-related properties, namely unlinkability (sometimes called untraceability),

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and anonymity. These two notions are informally defined in the ISO/IEC standard 15408 [2] as follows:

- Unlinkability aims at *ensuring that a user may make multiple uses of a service or resource without others being able to link these uses together.*
- Anonymity aims at *ensuring that a user may use a service or resource without disclosing its identity.*

Both are critical for instance for Radio-Frequency Identification Devices (RFID) and are thus extensively studied in that context (see, *e.g.* [46] for a survey of attacks on this type of protocols), but they are obviously not limited to it.

One extremely successful approach when designing and analyzing security protocols is the use of formal verification, *i.e.* the development of rigorous frameworks and techniques to analyze protocols. This approach has notably led to the discovery of a flaw in the Single-Sign-On protocol used *e.g.* by Google Apps. It has been shown that a malicious application could very easily access to any other application (*e.g.* Gmail or Google Calendar) of their users [10]. This flaw has been found when analyzing the protocol using formal methods, abstracting messages by a term algebra and using the **Avantssar** validation platform. Another example is a flaw on vote-privacy discovered during the formal and manual analysis of an electronic voting protocol [31]. All these results have been obtained using *formal symbolic models*, where most of the cryptographic details are ignored using abstract structures. The techniques used in symbolic models have become mature and several tools for protocol verification are nowadays available, *e.g.* the **Avantssar** platform [11], the **Tamarin** prover [41], and the **ProVerif** tool [18].

Unfortunately, most of these results and tools focus on trace properties, that is, statements that something bad never occurs on any execution trace of a protocol. Secrecy and authentication are typical examples of trace properties: a data remains confidential if, for any execution, the attacker is not able to produce the data. However, privacy properties like unlinkability and anonymity typically cannot be defined as trace properties. Instead, they are usually defined as the fact that an observer cannot distinguish between two situations, which requires a notion of behavioural equivalence. Based on such a notion of equivalence, several definitions of privacy-type properties have been proposed (*e.g.* [7,22] for unlinkability, and [33,12] for vote-privacy). In this paper, we consider the well-established definitions of strong unlinkability and anonymity as defined in [7]. They have notably been used to establish privacy for various protocols either by hand or using ad hoc encodings (*e.g.* eHealth protocol [35], mobile telephony [8,9]). We provide a brief comparison with alternative definitions in Section 3.3.

Considering an unbounded number of sessions, the problem of deciding whether a protocol satisfies an equivalence property is undecidable even for a very limited fragment of protocols (see, *e.g.* [29]). Bounding the number of sessions suffices to retrieve decidability for standard primitives (see, *e.g.* [15,28]). However, analysing a protocol for a fixed (often low) number of sessions does not allow to prove security. Moreover, in the case of equivalence properties, existing tools scale badly and can only analyse protocols for a very limited number of sessions, typically 2 or 3. Another approach consists in implementing a procedure that is not guaranteed to terminate. This is in particular the case of **ProVerif**, a well-established tool for checking security of protocols. **ProVerif** is able to check a strong notion of equivalence (called diff-equivalence) between processes that share the same structure. Despite recent improvements on diff-equivalence checking [27]

intended to prove unlinkability of the BAC protocol (used in e-passport), **ProVerif** still cannot be used off-the-shelf to establish unlinkability properties, and therefore cannot conclude on most of the case studies presented in Section 6. Recently, similar approaches have been implemented in two other tools, namely **Tamarin** [14] and **Maude-NPA** [43]. They are based on a notion of diff-equivalence, and therefore suffer from the same drawbacks.

Our contribution. We believe that looking at trace equivalence of any pair of protocols is a too general problem and that much progress can be expected when one focuses on a few privacy goals and a class of protocols only (yet large and generic enough). We follow this different approach. We aim at proposing sufficient conditions that can be automatically checked, and that imply unlinkability and anonymity for a large class of security protocols. The success of our solution will be measured by confronting it to many real-world case studies.

More precisely, we identify a large class of 2-party protocols (simple else branches, arbitrary cryptographic primitives) and we devise two conditions called *frame opacity* and *well-authentication* that imply unlinkability and anonymity for an unbounded number of sessions. We show how these two conditions can be automatically checked using *e.g.* the **ProVerif** tool, and we provide tool support for that. Using our tool **UKano** (built on top of **ProVerif**), we have automatically analysed several protocols, among them the Basic Access Control (BAC) protocol as well as the Password Authenticated Connection Establishment (PACE) protocol that are both used in e-passports. We notably establish the first proof of unlinkability for ABCDH [5] and for the BAC protocol followed by the Passive Authentication (PA) and Active Authentication (AA) protocols. We also report on an attack that we found on the PACE protocol, and another one that we found on the LAK protocol [40] whereas it is claimed untraceable in [46]. It happens that our conditions are rather tight, and we believe that the overall methodology and proof method could be used for other classes of protocols and other privacy goals.

Our sufficient conditions. We now give an intuitive overview of our two sufficient conditions, namely *frame opacity* and *well-authentication*. In order to do this, assume that we want to design a mutual authentication protocol between a tag T and a reader R based on symmetric encryption, and we want this protocol to be unlinkable. We assume that k is a symmetric key shared between T and R .

A first attempt to design such a protocol is presented using Alice & Bob notation as follows (n_R is a fresh nonce):

1. $R \rightarrow T : n_R$
2. $T \rightarrow R : \{n_R\}_k$

This first attempt based on a challenge-response scheme is actually linkable. Indeed, an active attacker who systematically intercepts the nonce n_R and replaces it by a constant will be able to infer whether the same tag has been used in different sessions or not by comparing the answers he receives. Here, the tag is linkable because, for a certain behaviour (possibly malicious) of the attacker, some relations between messages leak information about the agents that are involved in the execution. Our first condition, namely *frame opacity*, actually checks that all outputted messages have only relations that only depend on what is already observable. Such relations can therefore not be exploited by the attacker to learn anything new about the involved agents.

Our second attempt takes the previous attack into account and randomises the tag's response and should achieve mutual authentication by requiring that the reader must answer to the challenge n_T . This protocol can be as follows:

1. $R \rightarrow T : n_R$
2. $T \rightarrow R : \{n_R, n_T\}_k$
3. $R \rightarrow T : \{n_T\}_k$

Here, Alice & Bob notation shows its limit. It does not specify how the reader and the tag are supposed to check that the messages they received are of the expected form, and how they should react when the messages are not well formed. This has to be precisely defined, since unlinkability depends on it. For instance, assume the tag does not check that the message he receives at step 3 contains n_T , and aborts the session if the received message is not encrypted with its own k . In such an implementation, an active attacker can eavesdrop a message $\{n_T\}_k$ sent by R to a tag T , and try to inject this message at the third step of another session played by T' . The tag T' will react by either aborting or by continuing the execution of this protocol. Depending on the reaction of the tag, the attacker will be able to infer if T and T' are the same tag or not.

In this example, the attacker adopts a malicious behaviour that is not detected immediately by the tag who keeps executing the protocol. The fact that the tag passes successfully a conditional reveals crucial information about the agents that are involved in the execution. Our second condition, namely *well-authentication*, basically requires that when an execution deviates from the honest one, the agents that are involved cannot successfully pass a conditional, thus avoiding the leak of the binary information success/failure.

Our main theorem states that these two conditions, frame opacity and well-authentication, are actually sufficient to ensure both unlinkability and anonymity. This theorem is of interest as our two conditions are fundamentally simpler than the targeted properties: frame opacity can be expressed and established relying on diff-equivalence (without the aforementioned precision issue) and well-authentication is only a conjunction of reachability properties. In fact, they are both in the scope of existing automatic verification tools like **ProVerif** and **Tamarin**.

Some related work. The precision issue of diff-equivalence is well-known (acknowledged *e.g.* in [34,27,20,32]). So far, the main approach that has been developed to solve this issue consists in modifying the notion of diff-equivalence to get closer to trace equivalence. For instance, the swapping technique introduced in [34] and formally justified in [20] allows to relax constraints imposed by diff-equivalence in specific situations, namely in process algebras featuring a notion of phase, often used for modelling e-voting protocols. Besides, the limitation of the diff-equivalence w.r.t. conditional evaluations has been partially addressed in [27] by pushing away the evaluation of some conditionals into terms. Nevertheless, the problem remains in general and the limitation described above is not addressed by those works (incidentally, it is specifically acknowledged for the case of the BAC protocol in [27]). We have chosen to follow a novel approach in the same spirit as the one presented in [22]. However, [22] only considers a very restricted class of protocols (single-step protocols that only use hash functions), while we target more complex protocols.

This paper essentially subsumes the conference paper that has been published in 2016 [38]. Compared to that earlier work, we have greatly generalized the scope of our method and improved its mechanization. First, we consider more protocols, including protocols where one party has a

single identity (e.g. DAA) as well as protocols where sessions are executed sequentially instead of concurrently (e.g. e-passport scenarios). Second, we consider a much more general notion of frame opacity, which enables the analysis of more protocols. As a result of these two improvements, we could apply our method to more case studies (e.g. DAA, ABCDH).

Outline. In Section 2, we present our model inspired from the applied pi calculus as well as the class of protocols we consider. We then introduce in Section 3 the notion of trace equivalence that we then use to formally define the two privacy properties we study in this paper: unlinkability and anonymity. Our two conditions (frame opacity and well-authentication) and our main theorem are presented in Section 4. Finally, we discuss how to mechanize the verification of our conditions in Section 5 and present our case studies in Section 6, before concluding in Section 7. A detailed proof of our main result is provided in Appendix.

2. Modelling protocols

We model security protocols using a process algebra inspired from the applied pi calculus [4]. More specifically, we consider a calculus close to the one which is used in the **ProVerif** tool [19]. Participants are modeled as processes, and the communication between them is modeled by means of the exchange of messages that are represented by a term algebra.

2.1. Term algebra

We consider an infinite set \mathcal{N} of *names* which are used to represent keys and nonces, and two infinite and disjoint sets of *variables*, denoted \mathcal{X} and \mathcal{W} . Variables in \mathcal{X} will typically be used to refer to unknown parts of messages expected by participants, while variables in \mathcal{W} will be used to store messages learned by the attacker. We assume a *signature* Σ , i.e. a set of function symbols together with their arity, split into *constructor* and *destructor* symbols, i.e. $\Sigma = \Sigma_c \sqcup \Sigma_d$.

Given a signature \mathcal{F} and a set of initial data A , we denote by $\mathcal{T}(\mathcal{F}, A)$ the set of terms built from elements of A by applying function symbols in \mathcal{F} . Terms of $\mathcal{T}(\Sigma_c, \mathcal{N} \cup \mathcal{X})$ will be called *constructor terms*. We note $\text{vars}(u)$ the set of variables that occur in a term u . A *message* is a constructor term u that is *ground*, i.e. such that $\text{vars}(u) = \emptyset$. We denote by $\bar{x}, \bar{n}, \bar{u}, \bar{t}$ a (possibly empty) sequence of variables, names, messages, and terms respectively. We also sometimes write them (n_1, n_2, \dots) or simply n (when the sequence is reduced to one element). Substitutions are denoted by σ , the domain of a substitution is written $\text{dom}(\sigma)$, and the application of a substitution σ to a term u is written $u\sigma$. The *positions* of a term are defined as usual.

Example 1. Consider the following signature:

$$\Sigma = \{\text{enc}, \text{dec}, \langle \rangle, \text{proj}_1, \text{proj}_2, \oplus, 0, \text{eq}, \text{ok}\}.$$

The symbols **enc** and **dec** of arity 2 represent symmetric encryption and decryption. Pairing is modeled using $\langle \rangle$ of arity 2, and projection functions **proj**₁ and **proj**₂, both of arity 1. The function symbol \oplus of arity 2 and the constant 0 are used to model the exclusive or operator. Finally, we consider the symbol **eq** of arity 2 to model equality test, as well as the constant symbol **ok**. This signature is split into two parts: $\Sigma_c = \{\text{enc}, \langle \rangle, \oplus, 0, \text{ok}\}$, and $\Sigma_d = \{\text{dec}, \text{proj}_1, \text{proj}_2, \text{eq}\}$.

As in the process calculus presented in [19], constructor terms are subject to an equational theory; this has proved very useful for modelling algebraic properties of cryptographic primitives (see *e.g.* [30] for a survey). Formally, we consider a congruence $=_{\mathbf{E}}$ on $\mathcal{T}(\Sigma_c, \mathcal{N} \cup \mathcal{X})$, generated from a set of equations \mathbf{E} over $\mathcal{T}(\Sigma_c, \mathcal{X})$. Thus, this congruence relation is closed under substitution and renaming. We assume that it is not degenerate, *i.e.* there exist u, v such that $u \neq_{\mathbf{E}} v$.

Example 2. *To reflect the algebraic properties of the exclusive or operator, we may consider the equational theory generated by the following equations:*

$$x \oplus 0 = x \quad x \oplus x = 0 \quad x \oplus y = y \oplus x \quad (x \oplus y) \oplus z = x \oplus (y \oplus z)$$

In such a case, we have that $\text{enc}(a \oplus (b \oplus a), k) =_{\mathbf{E}} \text{enc}(b, k)$.

We also give a meaning to destructor symbols through the notion of *computation relation*. As explained below, a computation relation may be derived from a rewriting system but we prefer to not commit to a specific construction. Instead, we assume an arbitrary relation subject to a number of requirements, ensuring that the computation relation behaves naturally with respect to names, constructors, and the equational theory.

Definition 1. *A computation relation is a relation over $\mathcal{T}(\Sigma, \mathcal{N}) \times \mathcal{T}(\Sigma_c, \mathcal{N})$, denoted \Downarrow , that satisfies the following requirements:*

1. *if $n \in \mathcal{N}$, then $n \Downarrow n$;*
2. *if $f \in \Sigma_c$ is a symbol of arity k , and $t_1 \Downarrow u_1, \dots, t_k \Downarrow u_k$, then $f(t_1, \dots, t_k) \Downarrow f(u_1, \dots, u_k)$;*
3. *if $t \Downarrow u$ then $t\rho \Downarrow u\rho$ for any bijective renaming ρ ;*
4. *if t' is a context built from Σ and \mathcal{N} , $t \Downarrow u$, and $t'[u] \Downarrow v$ then $t'[t] \Downarrow v$;*
5. *if t' is a context built from Σ and \mathcal{N} , and t_1, t_2 are constructor terms such that $t_1 =_{\mathbf{E}} t_2$ and $t'[t_1] \Downarrow u_1$ for some u_1 , then $t'[t_2] \Downarrow u_2$ for some u_2 such that $u_1 =_{\mathbf{E}} u_2$;*
6. *if $t \Downarrow u_1$ then we have that $t \Downarrow u_2$ if, and only if, $u_1 =_{\mathbf{E}} u_2$.*

The last requirement expresses that the relation \Downarrow associates, to any ground term t , at most one message up to the equational theory \mathbf{E} . When no such message exists, we say that the *computation fails*; this is noted $t \not\Downarrow$. We may sometimes use directly $t \Downarrow$ as a message, when we know that the computation succeeds and the choice of representative is irrelevant.

A possible way to derive a computation relation is to consider an ordered set of rules of the form $\mathbf{g}(u_1, \dots, u_n) \rightarrow u$ where \mathbf{g} is a destructor, and $u, u_1, \dots, u_n \in \mathcal{T}(\Sigma_c, \mathcal{X})$. A ground term t can be rewritten into t' if there is a position p in t and a rule $\mathbf{g}(u_1, \dots, u_n) \rightarrow u$ such that $t|_p = \mathbf{g}(v_1, \dots, v_n)$ and $v_1 =_{\mathbf{E}} u_1\theta, \dots, v_n =_{\mathbf{E}} u_n\theta$ for some substitution θ , and $t' = t[u\theta]_p$ (*i.e.* t in which the subterm at position p has been replaced by $u\theta$). Moreover, we assume that $u_1\theta, \dots, u_n\theta$ as well as $u\theta$ are messages. In case there is more than one rule that can be applied at a given position p , we consider the one occurring first in the ordered set. We denote \rightarrow^* the reflexive and transitive closure of \rightarrow , and \Downarrow the relation induced by \rightarrow , *i.e.* $t \Downarrow u$ when $t \rightarrow^* u'$ and $u' =_{\mathbf{E}} u$.

Proving that an ordered set rewriting rules as defined above induces a computation relation is beyond the scope of this paper but the interested reader will find such a proof in [37].

Example 3. *The properties of symbols in Σ_d (Example 1) are reflected through the following rules:*

$$\text{dec}(\text{enc}(x, y), y) \rightarrow x \quad \text{eq}(x, x) \rightarrow \text{ok} \quad \text{proj}_i(\langle x_1, x_2 \rangle) \rightarrow x_i \quad \text{for } i \in \{1, 2\}$$

This rewriting system induces a computation relation. For instance, we have that:

$$\text{dec}(\text{enc}(c, a \oplus b), b \oplus a) \Downarrow c, \quad \text{dec}(\text{enc}(c, a \oplus b), b) \not\Downarrow, \text{ and } \quad \text{dec}(a, b) \oplus \text{dec}(a, b) \not\Downarrow.$$

Example 4. Ordered rewriting rules are expressive enough to define a destructor symbol neq such that $\text{neq}(u, v) \Downarrow \text{yes}$ if, and only if, u and v can be reduced to messages that are not equal modulo E . It suffices to consider $\text{neq}(x, x) \rightarrow \text{no}$ and $\text{neq}(x, y) \rightarrow \text{yes}$ (in this order) with $\text{yes}, \text{no} \in \Sigma_c$.

For modelling purposes, we split the signature Σ into two parts, namely Σ_{pub} and Σ_{priv} . An attacker builds his own messages by applying public function symbols to terms he already knows and that are available through variables in \mathcal{W} . Formally, a computation done by the attacker is a *recipe*, i.e. a term in $\mathcal{T}(\Sigma_{\text{pub}}, \mathcal{W})$. Recipes will be denoted by R, M, N . Note that, although we do not give the attacker the ability to generate fresh names to use in recipes, we obtain essentially the same capability by assuming an infinite supply of public constants in $\Sigma_c \cap \Sigma_{\text{pub}}$.

2.2. Process algebra

We now define the syntax and semantics of the process algebra we use to model security protocols. We consider a calculus close to the one which is used in the **ProVerif** tool [19]. An important difference is that we only consider public channels. Our calculus also features, in addition to the usual replication (where an unbounded number of copies of a process are ran concurrently), a simple form of sequential composition and the associated *repetition* operation (where an unbounded number of copies of a process are ran sequentially, one after the other).

We consider a set \mathcal{C} of channel names that are assumed to be public. Protocols are modeled through processes using the following grammar:

$$\begin{array}{llll} P, Q := 0 & \text{null} & | (P \mid Q) & \text{parallel} & | !P & \text{replication} \\ & | \text{in}(c, x).P & \text{input} & | \text{new } \bar{n}.P & \text{restriction} & | iP & \text{repetition} \\ & | \text{out}(c, u).P & \text{output} & | \text{let } \bar{x} = \bar{t} \text{ in } P \text{ else } Q & \text{evaluation} & | P; Q & \text{sequence} \end{array}$$

where $c \in \mathcal{C}$, $x \in \mathcal{X}$, $n \in \mathcal{N}$, $u \in \mathcal{T}(\Sigma_c, \mathcal{N} \cup \mathcal{X})$, and \bar{x} and \bar{t} are two sequences of the same length, respectively over variables (\mathcal{X}) and terms ($\mathcal{T}(\Sigma, \mathcal{N} \cup \mathcal{X})$).

We write $fv(P)$ for the set of *free variables* of P , i.e. the set of variables that are not bound by an input or a let construct. A process P is ground if $fv(P) = \emptyset$. Similarly, we write $fn(P)$ for the set of *free names* of P , i.e. the set of names that are not bound by a new construct.

Most constructs are standard in process calculi. The process 0 does nothing and we sometimes omit it. The process $\text{in}(c, x).P$ expects a message m on channel c and then behaves like $P\{x \mapsto m\}$, i.e. P in which the (free) occurrences of x have been replaced by m . The process $\text{out}(c, u).P$ emits u on channel c , and then behaves like P . The process $P \mid Q$ runs P and Q in parallel. The process $\text{new } \bar{n}.P$ generates new names, binds it to \bar{n} , and continues as P .

The special construct $\text{let } \bar{x} = \bar{t} \text{ in } P \text{ else } Q$ combines several standard constructions, allowing one to write computations and conditionals compactly. Such a process tries to evaluate the sequence of terms \bar{t} and in case of success, i.e. when $\bar{t} \Downarrow \bar{u}$ for some messages \bar{u} , the process P in which \bar{x} are replaced by \bar{u} is executed; otherwise the process Q is executed. The goal of this construct is

to avoid nested **let** instructions to be able to define our class of protocols in a simple way later on. Note also that the **let** instruction together with the **eq** theory as defined in Example 3 can encode the usual conditional construction. Indeed, **let** $x = \text{eq}(u, v)$ **in** P **else** Q will execute P only if the computation succeeds on $\text{eq}(u, v)$, that is only if $u \Downarrow u'$, $v \Downarrow v'$, and $u' =_{\text{E}} v'$ for some messages u' and v' . For brevity, we sometimes omit **else** 0.

The process $!P$ executes P an arbitrary number of times (in parallel). The last two constructs correspond to sequential compositions. The process $(P; Q)$ behaves like P at first, and after the complete execution of P it behaves like Q . The process iP executes P an arbitrary number of times in sequence, intuitively corresponding to $(P; P; P; \dots)$. Such constructions are known to be problematic in process calculi. Our goal here is however quite modest: as will be visible in our operational semantics, our sequential composition is only meaningful for restricted processes. It could in fact be defined using recursion, but there is no point here to consider general recursion: our study is going to restrict to a simple class of protocols that would immediately exclude it.

Example 5. We consider the RFID protocol due to Feldhofer et al. as described in [36] and which can be presented using Alice & Bob notation as follows:

1. $I \rightarrow R : n_I$
2. $R \rightarrow I : \{n_I, n_R\}_k$
3. $I \rightarrow R : \{n_R, n_I\}_k$

The protocol is between an initiator I (the reader) and a responder R (the tag) that share a symmetric key k . We consider the term algebra introduced in Example 3. The protocol is modelled by the parallel composition of P_I and P_R , corresponding respectively to the roles I and R .

$$P_{\text{Fh}} := \text{new } k. (\text{new } n_I. P_I \mid \text{new } n_R. P_R)$$

where P_I and P_R are defined as follows, with $u = \text{dec}(x_1, k)$:

$$\begin{array}{ll} P_I := \text{out}(c_I, n_I). & P_R := \text{in}(c_R, y_1). \\ \text{in}(c_I, x_1). & \text{out}(c_R, \text{enc}(\langle y_1, n_R \rangle, k)). \\ \text{let } x_2, x_3 = \text{eq}(n_I, \text{proj}_1(u)), \text{proj}_2(u) \text{ in} & \text{in}(c_R, y_2). \\ \text{out}(c_I, \text{enc}(\langle x_3, n_I \rangle, k)) & \text{let } y_3 = \text{eq}(y_2, \text{enc}(\langle n_R, y_1 \rangle, k)) \text{ in } 0 \end{array}$$

The operational semantics of processes is given by a labelled transition system over *configurations* (denoted by K) which are pairs $(\mathcal{P}; \phi)$ where:

- \mathcal{P} is a multiset of ground processes where null processes are implicitly removed;
- $\phi = \{w_1 \mapsto u_1, \dots, w_n \mapsto u_n\}$ is a *frame*, i.e. a substitution where w_1, \dots, w_n are variables in \mathcal{W} , and u_1, \dots, u_n are messages.

We often write $P \cup \mathcal{P}$ instead of $\{P\} \cup \mathcal{P}$. The terms in ϕ represent the messages that are known by the attacker. Given a configuration K , $\phi(K)$ denotes its second component. Sometimes, we consider processes as configurations, in such cases, the corresponding frame is \emptyset .

The operational semantics of a process is given by the relation $\xrightarrow{\alpha}$ defined as the least relation over configurations satisfying the rules in Figure 1. The rules are quite standard and correspond to the intuitive meaning given previously. The rule IN allows the attacker to send on channel c a message as soon as it is the result of a computation done by applying public function symbols on messages that are in his current knowledge. The rule OUT corresponds to the output of a

IN	$(\text{in}(c, x).P \cup \mathcal{P}; \phi) \xrightarrow{\text{in}(c, R)} (P\{x \mapsto u\} \cup \mathcal{P}; \phi)$ where R is a recipe such that $R\phi \Downarrow u$ for some message u	
OUT	$(\text{out}(c, u).P \cup \mathcal{P}; \phi) \xrightarrow{\text{out}(c, w)} (P \cup \mathcal{P}; \phi \cup \{w \mapsto u\})$ with w a fresh variable in \mathcal{W}	
PAR	$(\{P_1 \mid P_2\} \cup \mathcal{P}; \phi) \xrightarrow{\tau} (\{P_1, P_2\} \cup \mathcal{P}; \phi)$	
NEW	$(\text{new } \bar{n}.P \cup \mathcal{P}; \phi) \xrightarrow{\tau} (P \cup \mathcal{P}; \phi)$	where \bar{n} are fresh names from \mathcal{N}
REPL	$(!P \cup \mathcal{P}; \phi) \xrightarrow{\tau} (P \cup !P \cup \mathcal{P}; \phi)$	
THEN	$(\text{let } \bar{x} = \bar{t} \text{ in } P \text{ else } Q \cup \mathcal{P}; \phi) \xrightarrow{\tau_{\text{then}}} (P\{\bar{x} \mapsto \bar{u}\} \cup \mathcal{P}; \phi)$	when $\bar{t} \Downarrow \bar{u}$ for some \bar{u}
ELSE	$(\text{let } \bar{x} = \bar{t} \text{ in } P \text{ else } Q \cup \mathcal{P}; \phi) \xrightarrow{\tau_{\text{else}}} (Q \cup \mathcal{P}; \phi)$	when $t_i \not\Downarrow$ for some $t_i \in \bar{t}$
REC	$(iP \cup \mathcal{P}; \phi) \xrightarrow{\tau} (\{P; iP\} \cup \mathcal{P}; \phi)$	
SEQ ₀	$(\{0; Q\} \cup \mathcal{P}; \phi) \xrightarrow{\tau} (Q \cup \mathcal{P}; \phi)$	
SEQ	$(\{P; Q\} \cup \mathcal{P}; \phi) \xrightarrow{\alpha} (\{P'; Q\} \cup \mathcal{P}; \phi')$	if $(\{P\}; \phi) \xrightarrow{\alpha} (\{P'\}; \phi')$

Fig. 1. Semantics for processes

term: the corresponding term is added to the frame of the current configuration, which means that the attacker gains access to it. The three next rules allow one to execute a restriction (generating a new name), unfold a replication, and split a parallel composition. The THEN and ELSE rules correspond to the evaluation of a sequence of terms $\bar{t} = t_1, \dots, t_n$; if this succeeds, *i.e.* if there exist messages u_1, \dots, u_n such that $t_1 \Downarrow u_1, \dots, t_n \Downarrow u_n$ then variables \bar{x} are bound to those messages, and P is executed; otherwise the process will continue with Q . The last three rules deal with sequential executions. Note that the process $(P; Q)$ may perform an action α when P does so, but only if it reduces to a single process P' after that. Hence, parallel compositions (and replications) are not executable on the left of a sequence (and inside repetitions).

We note that our semantics enjoys some expected properties. Reduction is stable by bijective renaming, thanks to Definition 1, item 3: if $K_1 \xrightarrow{\alpha} K_2$ then $K_1\rho \xrightarrow{\alpha} K_2\rho$ where ρ is a bijection over \mathcal{N} , applied here to processes and frames. It is also compatible with our equational theory, thanks to Definition 1, items 5 and 6: if $K_1 \xrightarrow{\alpha} K_2$ then $K'_1 \xrightarrow{\alpha} K'_2$ for any $K'_1 =_{\text{E}} K_1$ and $K'_2 =_{\text{E}} K_2$. By Definition 1, item 6, we also have that

$$(\mathcal{P}; \phi) \xrightarrow{\text{in}(c, R)} (\mathcal{P}'; \phi) \text{ and } R\phi \Downarrow =_{\text{E}} R'\phi \Downarrow \text{ yield } (\mathcal{P}; \phi) \xrightarrow{\text{in}(c, R')} (\mathcal{P}'; \phi) \text{ (modulo E).}$$

As usual, the relation $\xrightarrow{\alpha_1 \dots \alpha_n}$ between configurations (where $\alpha_1 \dots \alpha_n$ is a *trace*, *i.e.* a sequence of actions) is defined as the (labelled) reflexive and transitive closure of $\xrightarrow{\alpha}$.

Definition 2. *Input and output actions are called observable, while all other are unobservable. Given a trace tr we define $\text{obs}(\text{tr})$ to be the sub-sequence of observable actions of tr .*

We generally refer to τ , τ_{then} and τ_{else} as *unobservable actions*. It will become clear later on why we make a distinction when a process evolves using THEN or ELSE.

Example 6. Continuing Example 5. We have that $P_{\text{Fh}} \xrightarrow{\text{tr}} (\emptyset; \phi_0)$ where:

- $\text{tr} = \tau.\tau.\tau.\tau.\text{out}(c_I, w_1).\text{in}(c_R, w_1).\text{out}(c_R, w_2).\text{in}(c_I, w_2).\tau_{\text{then}}.\text{out}(c_I, w_3).\text{in}(c_R, w_3).\tau_{\text{then}};$
- $\phi_0 = \{w_1 \mapsto n'_I, w_2 \mapsto \text{enc}(\langle n'_I, n'_R \rangle, k'), w_3 \mapsto \text{enc}(\langle n'_R, n'_I \rangle, k')\}.$

The names k' , n'_I and n'_R are fresh names. Actually, this execution corresponds to a normal execution of one session of the protocol.

2.3. A generic class of two-party protocols

We aim to propose sufficient conditions to ensure unlinkability and anonymity for a generic class of two-party protocols. In this section, we define formally the class of protocols we are interested in. We consider two-party protocols that are therefore made of two roles called the initiator and responder role respectively. We assume a set \mathcal{L} of labels that will be used to name output actions in these roles, allowing us to identify outputs that are performed by a same syntactic output action. These labels have no effect on the semantics.

Definition 3. An initiator role is a ground process obtained using the following grammar:

$$P_I := 0 \mid \ell : \text{out}(c, u).P_R$$

where $c \in \mathcal{C}$, $u \in \mathcal{T}(\Sigma_c, \mathcal{N} \cup \mathcal{X})$, $\ell \in \mathcal{L}$, and P_R is obtained from the grammar of responder roles:

$$P_R := 0 \mid \text{in}(c, y).\text{let } \bar{x} = \bar{t} \text{ in } P_I \text{ else } 0 \mid \text{in}(c, y).\text{let } \bar{x} = \bar{t} \text{ in } P_I \text{ else } \ell : \text{out}(c', u')$$

where $c, c' \in \mathcal{C}$, $y \in \mathcal{X}$, \bar{x} (resp. \bar{t}) is a sequence of variables in \mathcal{X} (resp. terms in $\mathcal{T}(\Sigma, \mathcal{N} \cup \mathcal{X})$), $u' \in \mathcal{T}(\Sigma_c, \mathcal{N} \cup \mathcal{X})$, and $\ell \in \mathcal{L}$.

Intuitively, a role describes the actions performed by an agent. A responder role consists of waiting for an input and, depending on the outcome of a number of tests, the process will continue by sending a message and possibly waiting for another input, or stop possibly outputting an error message. An initiator behaves similarly but begins with an output. The grammar forces to add a conditional after each input. This is not a real restriction as it is always possible to add trivial conditionals with empty \bar{x} , and \bar{t} .

Example 7. Continuing our running example, P_I (resp. P_R) as defined in Example 5 is an initiator (resp. responder) role, up to the addition of a trivial conditional in role P_R and distinct labels ℓ_1 , ℓ_2 , and ℓ_3 to decorate output actions.

Then, a protocol notably consists of an initiator role and a responder role that can interact together producing an *honest trace*. Intuitively, an honest trace is a trace in which the attacker does not really interfere, and that allows the execution to progress without going into an else branch, which would intuitively correspond to a way to abort the protocol.

Definition 4. A trace tr (i.e. a sequence of actions) is honest for a frame ϕ if $\tau_{\text{else}} \notin \text{tr}$ and $\text{obs}(\text{tr})$ is of the form $\text{out}(_, w_0).\text{in}(_, R_0).\text{out}(_, w_1).\text{in}(_, R_1)\dots$ for arbitrary channel names, and such that $R_i\phi \Downarrow =_{\text{E}} w_i\phi$ for any action $\text{in}(_, R_i)$ occurring in tr .

In addition to the pair of initiator and responder roles, more information is needed in order to meaningfully define a protocol. Among the names that occur in these two roles, we need to distinguish those that correspond to long-term data (called *identity parameters* and denoted \bar{k} below) and those which shall be freshly generated at each session (called *session parameters*

and denoted \bar{n}_I and \bar{n}_R below). We will require that any free name of roles must be either a session or an identity parameter. We also need to know whether sessions (with the same identity parameters) can be executed *concurrently* or only *sequentially*. For instance, let us assume that the Feldhofer protocol is used in an access control scenario where all tags that are distributed to users have pairwise distinct identities. Assuming that tags cannot be cloned, it is probably more realistic to consider that a tag can be involved in at most one session at a particular time, *i.e.* a tag may run different sessions but only in sequence. Another concrete example where sessions are executed sequentially is the case of the e-passport application where a same passport cannot be involved in two different sessions concurrently. This is the purpose of the components \dagger_I and \dagger_R in the following definition. Moreover, we require that the process P_Π which models a single session of the protocol can produce an honest trace.

Definition 5. A protocol Π is a tuple $(\bar{k}, \bar{n}_I, \bar{n}_R, \dagger_I, \dagger_R, \mathcal{I}, \mathcal{R})$ where $\bar{k}, \bar{n}_I, \bar{n}_R$ are three disjoint sets of names, \mathcal{I} (resp. \mathcal{R}) is an initiator (resp. responder) role such that $\text{fn}(\mathcal{I}) \subseteq \bar{k} \sqcup \bar{n}_I$, $\text{fn}(\mathcal{R}) \subseteq \bar{k} \sqcup \bar{n}_R$, and $\dagger_I, \dagger_R \in \{!, i\}$. Labels of \mathcal{I} and \mathcal{R} must be pairwise distinct. Names \bar{k} (resp. $\bar{n}_I \sqcup \bar{n}_R$) are called identity parameters (resp. session parameters).

Given a protocol Π , we define $P_\Pi := \text{new } \bar{k}.(\text{new } \bar{n}_I.\mathcal{I} \mid \text{new } \bar{n}_R.\mathcal{R})$ and we assume that $P_\Pi \xrightarrow{\text{tr}_h} (\emptyset; \phi_h)$ for some frame ϕ_h and some trace tr_h that is honest for ϕ_h .

Given a protocol Π , we also associate another process \mathcal{M}_Π that represents the situation where the protocol can be executed by an arbitrary number of identities, with the possibility of executing an arbitrary number of sessions for a given identity. The formal definition differs slightly depending on whether identity parameters occur in both roles or only in the role \mathcal{I} (resp. \mathcal{R}).

Definition 6. Given a protocol $\Pi = (\bar{k}, \bar{n}_I, \bar{n}_R, \dagger_I, \dagger_R, \mathcal{I}, \mathcal{R})$, the process \mathcal{M}_Π is defined as follows:

- If $\bar{k} \cap \text{fn}(\mathcal{I}) \neq \emptyset$ and $\bar{k} \cap \text{fn}(\mathcal{R}) \neq \emptyset$, then $\mathcal{M}_\Pi = ! \text{new } \bar{k}.(\dagger_I \text{new } \bar{n}_I.\mathcal{I} \mid \dagger_R \text{new } \bar{n}_R.\mathcal{R})$;
- If $\bar{k} \cap \text{fn}(\mathcal{I}) = \emptyset$ and $\bar{k} \cap \text{fn}(\mathcal{R}) \neq \emptyset$, then $\mathcal{M}_\Pi = \dagger_I \text{new } \bar{n}_I.\mathcal{I} \mid ! \text{new } \bar{k}.\dagger_R \text{new } \bar{n}_R.\mathcal{R}$.

For the sake of simplicity, in case identity parameters only occur in one role, we assume that this role is the responder role. The omitted case where identity parameters occur only in the initiator role is very much similar. In fact, swapping the initiator and responder roles can also be formally achieved by adding an exchange of a fresh nonce at the beginning of the protocol under consideration. Note that the case where both $\bar{k} \cap \text{fn}(\mathcal{I})$ and $\bar{k} \cap \text{fn}(\mathcal{R})$ are empty means that no identity parameters are involved and therefore there is no issue regarding privacy.

Example 8. Let $\Pi_{\text{Fh}} = (k, n_I, n_R, !, !, P_I, P_R)$ with P_I and P_R as defined in Example 5 (up to the addition of a trivial conditional). Let $P_{\text{Fh}} = \text{new } k.(\text{new } n_I.P_I \mid \text{new } n_R.P_R)$, $\text{tr}_h = \text{tr}$ (up to the addition of an action τ_{then}), and $\phi_h = \phi_0$ as defined in Example 6. They satisfy the requirements stated in Definition 5, and therefore Π_{Fh} is a protocol according to our definition. For this protocol, the identity parameter k occurs both in the role P_I and P_R , and therefore we have that $\mathcal{M}_{\Pi_{\text{Fh}}} = ! \text{new } k.(! \text{new } n_I.P_I \mid ! \text{new } n_R.P_R)$.

For the purpose of illustrating our method and the use of the repetition operator, we will consider a variant of the Feldhofer protocol, described next.

Example 9. We consider a variant of the RFID protocol presented in Example 5. This protocol can be presented using Alice & Bob notation as follows:

1. $I \rightarrow R : n_I$
2. $R \rightarrow I : n_R, \{n_I\}_k^{r_R}$
3. $I \rightarrow R : \{n_R\}_k^{r_I}$

The protocol is between an initiator I (the reader) and a responder R (the tag) that share a symmetric key k . We consider here a randomised symmetric encryption scheme. We will see that there is a linkability attack in case concurrent sessions are possible, but this variant is actually safe (w.r.t. unlinkability) otherwise. We consider the computation relation induced by the empty set of equations, and the following rules:

$$\text{rdec}(\text{renc}(x, y, z), y) \rightarrow x \quad \text{eq}(x, x) \rightarrow \text{ok} \quad \text{proj}_i(\langle x_1, x_2 \rangle) \rightarrow x_i \quad \text{for } i \in \{1, 2\}.$$

The processes modelling the initiator and the responder roles are as follows:

$$\begin{array}{ll} P'_I := \text{out}(c_I, n_I). & P'_R := \text{in}(c_R, y_1). \\ \text{in}(c_I, x_1). & \text{out}(c_R, \langle n_R, \text{renc}(y_1, k, r_R) \rangle). \\ \text{let } x_2, x_3 = \text{eq}(n_I, \text{rdec}(\text{proj}_2(x_1), k)), \text{proj}_1(x_1) \text{ in} & \text{in}(c_R, y_2). \\ \text{out}(c_I, \text{renc}(x_3, k, r_I)) & \text{let } y_3 = \text{eq}(n_R, \text{rdec}(y_2, k)) \text{ in } 0 \end{array}$$

The tuple $\Pi_{\text{Fh}'}^i = (k, (n_I, r_I), (n_R, r_R), i, i, P'_I, P'_R)$ is a protocol according to Definition 5. For this protocol, we have again that k occurs both in the roles P'_R and P'_I , and therefore:

$$\mathcal{M}_{\Pi_{\text{Fh}'}^i} = ! \text{new } k. (i \text{ new } (n_I, r_I). P'_I \mid i \text{ new } (n_R, r_R). P'_R).$$

As a last example, we will consider one for which identity parameters only occur in one role. This example can be seen as a simplified version of the Direct Anonymous Attestation (DAA) sign protocol that will be detailed in Section 6.

Example 10. We consider a simplified version of the protocol DAA sign (adapted from [44]). Note that a comprehensive analysis of the protocol DAA sign (as well as the protocol DAA join) will be conducted in Section 6. Before describing the protocol itself, we introduce the term algebra that will allow us to model the signature and zero knowledge proofs used in that protocol. We consider:

- $\Sigma_c = \{\text{sign}, \text{zk}, \text{pk}, \langle \rangle, \text{tuple}, \text{ok}, \text{sk}_I, \text{error}\}$, and
- $\Sigma_d = \{\text{check}_{\text{sign}}, \text{check}_{\text{zk}}, \text{public}_{\text{zk}}, \text{proj}_1, \text{proj}_2, \text{proj}_1^4, \text{proj}_2^4, \text{proj}_3^4, \text{proj}_4^4\}$.

We consider the computation relation induced by the empty set of equations, and the rules:

$$\begin{array}{ll} \text{check}_{\text{sign}}(\text{sign}(x, y), \text{pk}(y)) \rightarrow x & \text{proj}_i(\langle y_1, y_2 \rangle) \rightarrow y_i \quad i \in \{1, 2\} \\ \text{check}_{\text{zk}}(\text{zk}(\text{sign}(\langle x_k, x_{id} \rangle, z_{\text{sk}}), x_k, \text{tuple}(y_1, y_2, y_3, \text{pk}(z_{\text{sk}})))) \rightarrow \text{ok} & \\ \text{public}_{\text{zk}}(\text{zk}(x, y, z)) \rightarrow z & \text{proj}_i^4(\text{tuple}(y_1, y_2, y_3, y_4)) \rightarrow y_i \quad i \in \{1, 2, 3, 4\} \end{array}$$

The protocol is between a client C (the responder) and a verifier V (the initiator). The client is willing to sign a message m using a credential issued by some issuer and then he has to convince V that the latter signature is genuine. The client C has a long-term secret key k_C , an identity id_C , and some credential $\text{cred}_C = \text{sign}(\langle k_C, id_C \rangle, \text{sk}_I)$ issued by some issuer I having sk_I

as a long-term signature key. Such a credential would be typically obtained once for all through a protocol similar to DAA join. We give below an Alice & Bob description of the protocol:

1. $V \rightarrow C : n_V$
2. $C \rightarrow V : \text{zk}(\text{cred}_C, k_C, \text{tuple}(n_V, n_C, m, \text{pk}(\text{sk}_I)))$

The verifier starts by challenging the client with a fresh nonce, the latter then sends a complex zero-knowledge proof bound to this challenge proving that he knows a credential from the expected issuer bound to the secret k_C he knows. Before accepting this zero-knowledge proof, the verifier V (i) checks the validity of the zero-knowledge proof using the check_{zk} operator, and (ii) verifies that this proof is bound to the challenge n_V and to the public key of I using the $\text{public}_{\text{zk}}$ operator. The processes P_C and P_V are defined as follows:

$$P_V := \text{out}(c_V, n_V). \\ \text{in}(c_V, x_1). \\ \text{let } x_2, x_3, x_4 = \\ \text{eq}(\text{check}_{\text{zk}}(x_1), \text{ok}), \text{eq}(\text{proj}_1^4(\text{public}_{\text{zk}}(x_1)), n_V), \text{eq}(\text{proj}_4^4(\text{public}_{\text{zk}}(x_1)), \text{pk}(\text{sk}_I)) \text{ in } 0 \\ \text{else out}(c_V, \text{error})$$

$$P_C := \text{in}(c_R, y_1). \\ \text{out}(c_R, \text{zk}(\text{sign}(\langle k_C, id_C \rangle, \text{sk}_I), k_C, \text{tuple}(y_1, n_C, m, \text{pk}(\text{sk}_I)))).$$

This protocol falls in our class: the two parties being the verifier V and the client C . The tuple $\Pi_{\text{DAA}} = ((k_C, id_C), n_V, (n_C, m), !, !, P_V, P_C)$ is a protocol according to our Definition 5. We have that k_C or id_C only occur in P_C , and therefore following Definition 6, we have that:

$$\mathcal{M}_{\Pi_{\text{DAA}}} = (! \text{new } n_V. P_V) \mid (! \text{new } (k_C, id_C). ! \text{new } (n_C, m). P_C)$$

This models infinitely many different clients that may take part to infinitely many sessions of the protocol with any verifier that executes always the same role (he has no proper identity). We consider here a scenario where sessions can be executed concurrently.

Discussion about shared and non-shared protocols. As shown in Definition 6, we distinguish two cases depending on whether (i) both roles use identity parameters (i.e. when $fn(\mathcal{I}) \cap \bar{k} \neq \emptyset$ and $fn(\mathcal{R}) \cap \bar{k} \neq \emptyset$) or (ii) only one role uses identity parameters (i.e. when $fn(\mathcal{I}) \cap \bar{k} = \emptyset$ and $fn(\mathcal{R}) \cap \bar{k} \neq \emptyset$, the other case being symmetrical). The case (i) corresponds to the case where we should consider an arbitrary number of users for each role, whereas regarding case (ii) it is sufficient to consider an arbitrary number of users for role \mathcal{R} only. In addition to this distinction, note that there are two different kinds of protocols that lie in class (i):

(i-a) The *shared case* when $fn(\mathcal{I}) \cap fn(\mathcal{R}) \neq \emptyset$. In such a situation, roles \mathcal{I} and \mathcal{R} share names in $fn(\mathcal{I}) \cap fn(\mathcal{R})$. In practice, this shared knowledge may have been established in various ways such as by using prior protocols, using another communication channel (e.g. optical scan of a password as it is done with e-passports, use of PIN codes) or by retrieving the identity from a database that matches the first received message as it is often done with RFID protocols. For such protocols, it is expected that an initiator user and a responder user can communicate successfully producing an honest execution *only if* they have the same identity (i.e. they share the same names \bar{k}).

(i-b) The *non-shared case* when $fn(\mathcal{I}) \cap fn(\mathcal{R}) = \emptyset$. In such a case, both roles do not share any prior knowledge, and it is therefore expected that an initiator and a responder can communicate successfully producing an honest execution whatever their identities.

Unlinkability and anonymity will be uniformly expressed for the cases (i-a) and (i-b) but our sufficient conditions will slightly differ depending on the case under study.

3. Modelling security properties

This section is dedicated to the definition of the security properties we seek to verify on protocols: unlinkability and anonymity. Those properties are defined using the notion of *trace equivalence* which relates indistinguishable processes.

3.1. Trace equivalence

Intuitively, two configurations are trace equivalent if an attacker cannot tell whether he is interacting with one or the other. Before formally defining this notion, we first introduce a notion of equivalence between frames, called *static equivalence*.

Definition 7. A frame ϕ is statically included in ϕ' when $dom(\phi) = dom(\phi')$, and

- for any recipe R such that $R\phi \Downarrow u$ for some u , we have that $R\phi' \Downarrow u'$ for some u' ;
- for any recipes R_1, R_2 such that $R_1\phi \Downarrow u_1$, $R_2\phi \Downarrow u_2$, and $u_1 =_{\text{E}} u_2$, we have that $R_1\phi' \Downarrow =_{\text{E}} R_2\phi' \Downarrow$, i.e. there exist v_1, v_2 such that $R_1\phi' \Downarrow v_1$, $R_2\phi' \Downarrow v_2$, and $v_1 =_{\text{E}} v_2$.

Two frames ϕ and ϕ' are in static equivalence, written $\phi \sim \phi'$, if the two static inclusions hold.

Intuitively, an attacker can distinguish two frames if he is able to perform some computation (or a test) that succeeds in ϕ and fails in ϕ' (or the converse).

Example 11. Let ϕ_0 be the frame given in Example 6, we have that $\phi_0 \sqcup \{w_4 \mapsto k'\} \not\sim \phi_0 \sqcup \{w_4 \mapsto k''\}$. An attacker may observe a difference relying on the computation $R = \text{dec}(w_2, w_4)$.

Then, *trace equivalence* is the active counterpart of static equivalence, taking into account the fact that the attacker may interfere during the execution of the process. In order to define this, we first introduce $\text{trace}(K)$ for a configuration $K = (\mathcal{P}; \phi)$:

$$\text{trace}(K) = \{(\text{tr}, \phi') \mid (\mathcal{P}, \phi) \xrightarrow{\text{tr}} (\mathcal{P}'; \phi') \text{ for some configuration } (\mathcal{P}'; \phi')\}.$$

Definition 8. Let K and K' be two configurations. We say that K is trace included in K' , written $K \sqsubseteq K'$, when, for any $(\text{tr}, \phi) \in \text{trace}(K)$ there exists $(\text{tr}', \phi') \in \text{trace}(K')$ such that $\text{obs}(\text{tr}') = \text{obs}(\text{tr})$ and $\phi \sim \phi'$. They are in trace equivalence, written $K \approx K'$, when $K \sqsubseteq K'$ and $K' \sqsubseteq K$.

Example 12. Resuming Example 8, we may be interested in checking whether the configurations $K = (!P_{\Pi_{\text{Fh}}}; \emptyset)$ and $K' = (\mathcal{M}_{\Pi_{\text{Fh}}}; \emptyset)$ are in trace equivalence. This equivalence models the fact that Π_{Fh} is unlinkable: each session of the protocol appears to an attacker as if it has been initiated by a different tag, since a given tag can perform at most one session in the idealized scenario K . This equivalence actually holds. It is non-trivial, and cannot be established using existing verification tools such as ProVerif or Tamarin. The technique developed in this paper will notably allow one to establish it automatically.

3.2. Security properties under study

In this paper, we focus on two privacy-related properties, namely *unlinkability* and *anonymity*.

3.2.1. Unlinkability

According to the ISO/IEC standard 15408 [2], unlinkability aims at ensuring that a user may make multiple uses of a service or a resource without others being able to link these uses together. In terms of our modelling, a protocol preserves unlinkability if any two sessions of a same role look to an outsider as if they have been executed with different identity names. In other words, an ideal version of the protocol with respect to unlinkability, allows the roles \mathcal{I} and \mathcal{R} to be executed at most once for each identity names. An outside observer should then not be able to tell the difference between the original protocol and the ideal version of this protocol.

In order to precisely define this notion, we have to formally define this ideal version of a protocol Π . This ideal version, denoted \mathcal{S}_Π , represents an arbitrary number of agents that can at most execute one session each. Such a process is obtained from \mathcal{M}_Π by simply removing the symbols $!$ and i that are in the scope of identity names. Indeed, those constructs enable each identity to execute an arbitrary number of sessions (respectively concurrently and sequentially). Formally, depending on whether identity names occur in both roles, or only in the initiator role, this leads to slightly different definitions.

Definition 9. Given a protocol $\Pi = (\bar{k}, \bar{n}_I, \bar{n}_R, \dagger_I, \dagger_R, \mathcal{I}, \mathcal{R})$, the process \mathcal{S}_Π is defined as follows:

- If $\bar{k} \cap \text{fn}(\mathcal{I}) \neq \emptyset$ and $\bar{k} \cap \text{fn}(\mathcal{R}) \neq \emptyset$, then $\mathcal{S}_\Pi := ! \text{new } \bar{k}.(\text{new } \bar{n}_I.\mathcal{I} \mid \text{new } \bar{n}_R.\mathcal{R})$;
- If $\bar{k} \cap \text{fn}(\mathcal{I}) = \emptyset$ and $\bar{k} \cap \text{fn}(\mathcal{R}) \neq \emptyset$, then $\mathcal{S}_\Pi := \dagger_I \text{new } \bar{n}_I.\mathcal{I} \mid ! \text{new } \bar{k}.\text{new } \bar{n}_R.\mathcal{R}$.

Unlinkability is defined as a trace equivalence between \mathcal{S}_Π (where each identity can execute at most one session) and \mathcal{M}_Π (where each identity can execute an arbitrary number of sessions).

Definition 10. A protocol $\Pi = (\bar{k}, \bar{n}_I, \bar{n}_R, \dagger_I, \dagger_R, \mathcal{I}, \mathcal{R})$ ensures unlinkability if $\mathcal{M}_\Pi \approx \mathcal{S}_\Pi$.

Example 13. Going back to our running example (Example 8), unlinkability is expressed through the equivalence given in Example 12 and recalled below:

$$! \text{new } k.(! \text{new } n_I.P_I \mid ! \text{new } n_R.P_R) \approx ! \text{new } k.(\text{new } n_I.P_I \mid \text{new } n_R.P_R).$$

This intuitively represents the fact that the real situation where a tag and a reader may execute many sessions in parallel is indistinguishable from an idealized one where a given tag and a given reader can execute at most one session for each identity.

Although unlinkability of only one role (e.g. the tag for RFID protocols) is often considered in the literature (including [7]), we consider a stronger notion here since both roles are treated symmetrically. As illustrated through the case studies developed in Section 6 (see Sections 6.2 and 6.4), this is actually needed to not miss some practical attacks.

Example 14. We consider the variant of the Feldhofer protocol as described in Example 9. However, for illustrative purposes, we consider $\Pi_{\text{FH}}^! := (k, (n_I, r_I), (n_R, r_R), !, !, P_I', P_R')$, i.e. a situation where concurrent sessions are authorised. We may be interested in checking unlinkability as in Example 13, i.e. whether the following equivalence holds or not:

$$! \text{new } k.(\text{new } (n_I, r_I).P_I' \mid \text{new } (n_R, r_R).P_R') \approx ! \text{new } k.(! \text{new } (n_I, r_I).P_I' \mid ! \text{new } (n_R, r_R).P_R')$$

Actually, this equivalence does not hold. When concurrent sessions are authorised, an attacker can interfere and swap messages coming from two different parallel sessions. Performing these swaps, the two sessions will end correctly if, and only if, the keys that are involved in both sessions are the same. Such a scenario, depicted in Figure 2 (which is possible on the right-hand side) cannot be mimicked on the left-hand side (each tag can execute only once). Therefore the attacker observes that such an interaction is possible whereas this scenario has no counterpart in the single session scenario. In practice, this can be very harmful when e.g. tags are distributed among distinct groups (e.g. for access control policies) sharing each the same key k . By interacting with two tags, the attacker would then be able to know if they belong to the same group. The attacker would thus have the ability to trace a group (rather than individual tags); we still consider the former as unlinkability attack.

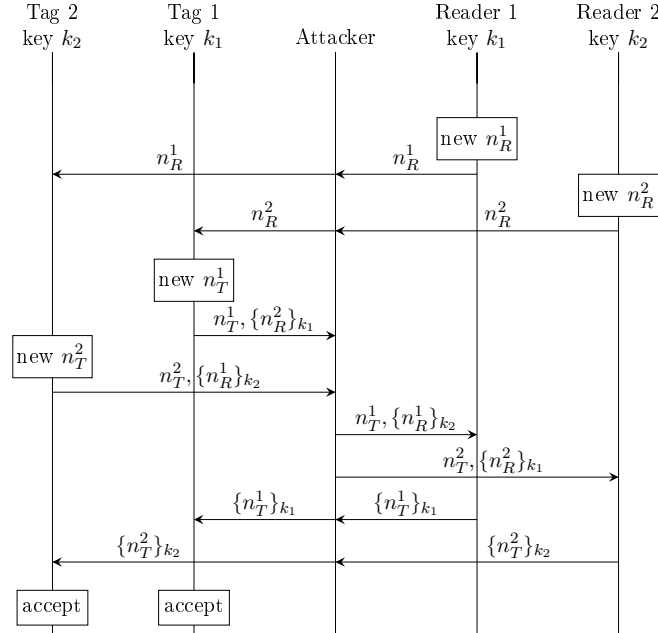


Fig. 2. A scenario involving two concurrent sessions (possible only if $k_1 = k_2$).

Now, coming back to the variant of the Feldhofer protocol as described in Example 9 (with sessions running sequentially only), it can be shown relying on the technique developed in this paper that unlinkability holds. We have that:

$$! \text{new } k. (\text{new } (n_I, r_I). P'_I \mid \text{new } (n_R, r_R). P'_R) \approx ! \text{new } k. (i \text{ new } (n_I, r_I). P'_I \mid i \text{ new } (n_R, r_R). P'_R)$$

3.2.2. Anonymity

According to the ISO/IEC standard 15408 [2], anonymity aims at ensuring that a user may use a service or a resource without disclosing its identity. In terms of our modelling, a protocol preserves anonymity of some identities $\overline{id} \subseteq k$, if a session executed with some particular (public) identities id_0 looks to an outsider as if it has been executed with different identity names. In other words, an outside observer should not be able to tell the difference between the original

protocol and a version of the protocol where the attacker knows that specific roles \mathcal{I} and \mathcal{R} with identities id_0 (known by the attacker) are present.

Definition 11. Given a protocol $\Pi = (\bar{k}, \bar{n}_I, \bar{n}_R, \dagger_I, \dagger_R, \mathcal{I}, \mathcal{R})$, and $\bar{id} \subseteq \bar{k}$, the process $\mathcal{M}_{\Pi, \bar{id}}$ is defined as follows:

- If $\bar{k} \cap \text{fn}(\mathcal{I}) \neq \emptyset$ and $\bar{k} \cap \text{fn}(\mathcal{R}) \neq \emptyset$, then $\mathcal{M}_{\Pi, \bar{id}} := \mathcal{M}_{\Pi} \mid \text{new } \bar{k}.(\dagger_I \text{new } \bar{n}_I. \mathcal{I}_0 \mid \dagger_R \text{new } \bar{n}_R. \mathcal{R}_0)$.
- If $\bar{k} \cap \text{fn}(\mathcal{I}) = \emptyset$ and $\bar{k} \cap \text{fn}(\mathcal{R}) \neq \emptyset$, then $\mathcal{M}_{\Pi, \bar{id}} := \mathcal{M}_{\Pi} \mid \text{new } \bar{k}. \dagger_R \text{new } \bar{n}_R. \mathcal{R}_0$.

where $\mathcal{I}_0 = \mathcal{I}\{\bar{id} \mapsto \bar{id}_0\}$ and $\mathcal{R}_0 = \mathcal{R}\{\bar{id} \mapsto \bar{id}_0\}$ for some fresh public constants \bar{id}_0 .

Definition 12. Let $\Pi = (\bar{k}, \bar{n}_I, \bar{n}_R, \dagger_I, \dagger_R, \mathcal{I}, \mathcal{R})$, and $\bar{id} \subseteq \bar{k}$. We say that Π ensures anonymity w.r.t. \bar{id} if $\mathcal{M}_{\Pi, \bar{id}} \approx \mathcal{M}_{\Pi}$.

Example 15. Going back to Example 10, anonymity w.r.t. identity of the client (i.e. id_C) is expressed through the following equivalence:

$$\begin{aligned} & ! \text{new } n_V. P_V \mid (! \text{new } (k_C, \text{id}_C). ! \text{new } (n_C, m). P_C) \mid (\text{new } (k_C, \text{id}_C). ! \text{new } (n_C, m). P_C\{\text{id}_C \mapsto \text{id}_0\}) \\ & \approx ! \text{new } n_V. P_V \mid (! \text{new } (k_C, \text{id}_C). ! \text{new } (n_C, m). P_C) \end{aligned}$$

This intuitively represents the fact that the situation in which a specific client with some known identity id_0 may execute some sessions is indistinguishable from a situation in which this client is not present at all. Therefore, if these two situations are indeed indistinguishable from the point of view of the attacker, it would mean that there is no way for the attacker to deduce whether a client with a specific identity is present or not.

3.3. Discussion

The definitions we proposed are variations of the ones proposed in [7]. In particular, they all share the same pattern: we compare some process modelling real usage of the protocol with another process modelling an idealised version of the system. We may note that we consider here the notion of trace equivalence instead of the stronger notion of labeled bisimilarity used in [7].

A flurry of alternative definitions of unlinkability have been proposed in the literature (see, e.g. [23,21] for a comparison). Among the strongest ones, various game-based formulations have been considered, both in the computational and symbolic models. Some of these definitions, unlike our definition of unlinkability, can be verified directly in **ProVerif** using the notion of diff-equivalence [13].

Game-based definition. We will not give any formal definition but instead briefly give its general idea. In such a definition, the following game is considered:

1. *Learning phase:* During this phase, the attacker can trigger an arbitrary number of sessions of the two roles (namely tag and reader) with the identity of his choice. This allows him to gain some knowledge. Eventually, the attacker chooses to end the learning phase and enter the second phase.
2. *Guessing phase:* The challenger chooses an identity x among two distinguished identities id_1 and id_2 . The attacker is allowed to interact again (an arbitrary number of times) with roles of x , or of identities other than id_1 and id_2 .

The attacker wins the game if he can infer whether x is id_1 or id_2 , *i.e.* if he is able to distinguish between these two scenarios. This is typically the kind of scenario that can be checked relying on the diff-equivalence notion implemented in several automatic tools (*e.g.* ProVerif, Tamarin). However, as illustrated by the following example, we would like to stress that such game-based definitions do not imply unlinkability as considered in this paper.

Example 16. We consider a protocol between a tag T and a reader R sharing a symmetric key k . We consider that sessions can be executed in parallel, and we assume that T aborts in case the nonce n_R he receives is equal to the nonce n_T he sent previously (in the same session).

1. $T \rightarrow R : \{n_T\}_k$
2. $R \rightarrow T : \{n_R\}_k$
3. $T \rightarrow R : \{n_R \oplus n_T\}_k$

We consider the term algebra introduced in Example 1, and the equational theory introduced in Example 2 with in addition the equation $\text{dec}(\text{enc}(x,y),y) = x$. To show that the property formally stated in Definition 10 does not hold, consider the following scenario.

- | | |
|--|--|
| 1. $T \rightarrow R : \{n_T\}_k$ | 1'. $T' \rightarrow R : \{n'_T\}_k$ |
| 2. $I(R) \rightarrow T : \{n'_T\}_k$ | 2'. $I(R) \rightarrow T' : \{n_T\}_k$ |
| 3. $T \rightarrow R : \{n'_T \oplus n_T\}_k$ | 3'. $T' \rightarrow R : \{n_T \oplus n'_T\}_k$ |

A same tag starts two sessions¹ and therefore generates two nonces n_T and n'_T . The attacker answers to these requests by sending back the two encrypted messages to the tag who will accept both of them, and sends on the network two messages that are actually equal (the exclusive or operator is commutative). Therefore the attacker observes a test, namely the equality between the last two messages, which has no counterpart in the single session scenario. Therefore, this protocol does not ensure unlinkability. In practice, this can be very harmful. Suppose, for example, that tags are distributed among distinct groups (*e.g.* for access control policies) sharing each the same key k . By interacting with two tags, the attacker would then be able to know if they belong to the same group and thus be able to trace groups.

To the best of our knowledge, all the existing game-based variants of unlinkability that are amenable to automation relying on the diff-equivalence notion suffer from this problem. We may note that the attack described in Example 14 is not captured when considering the game-based version of unlinkability. This protocol can even be proved secure using ProVerif when considering the game-based version of unlinkability while it suffers from the attack depicted in Figure 2.

4. Our approach

We now define our two conditions, namely frame opacity and well-authentication, and our result which states that these conditions are sufficient to ensure unlinkability and anonymity as

¹This is possible if different *physical* tags share the same identity (*e.g.* as it may be the case in access control scenarios). In such a case, it may happen that two different *physical* tags are running two sessions concurrently.

defined in Section 3. Before doing that, we shall introduce annotations in the semantics of our processes, in order to ease their analysis.

4.1. Annotations

We shall now define an annotated semantics whose transitions are equipped with more informative actions. The annotated actions will feature labels identifying which concurrent process has performed the action. This will allow us to identify which specific agent (with some specific identity and session names) performed some action.

Given a protocol $\Pi = (\bar{k}, \bar{n}_I, \bar{n}_R, \dagger_I, \dagger_R, \mathcal{I}, \mathcal{R})$ and $\bar{id} \subseteq \bar{k}$, consider any execution of $\mathcal{M}_{\Pi, \bar{id}}$, \mathcal{M}_{Π} or \mathcal{S}_{Π} . In such an execution, τ actions are solely used to create new agents (*i.e.* instantiations of \mathcal{I} and \mathcal{R} with new names or constants from id_0) by unfolding replications (*i.e.* !) or repetitions (*i.e.* i), breaking parallel compositions or choosing fresh session and identity names. Actions other than τ (that is, input, output and conditionals) are then only performed by the created agents. We say that an agent is either an instantiation of one of the two roles with some identity and session parameters, or its continuation after the execution of some actions. When $\dagger_A = !$, agents of role A are only found at toplevel in the multiset of processes. When $\dagger_A = i$, they may be followed by another process. For instance, in traces of \mathcal{M}_{Π} when $\dagger_I = i$, newly created initiator agents occur on the left of the sequence in processes of the form $\mathcal{I}\{\bar{k} \mapsto \bar{l}, \bar{n}_I \mapsto \bar{n}\}; i \text{ new } \bar{m}. \mathcal{I}\{\bar{k} \mapsto \bar{l}, \bar{n}_I \mapsto \bar{m}\}$.

The previous remark allows us to define an *annotated semantics* for our processes of interest. We consider *annotations* of the form $A(\bar{k}, \bar{n})$ where $A \in \{I, R\}$ and \bar{k}, \bar{n} are sequences of names, or constants from id_0 . Annotations are noted with the letter a , and the set of annotations is noted \mathcal{A} . We can then define an annotated semantics, where agents are decorated by such annotations, indicating their identity and session parameters. An agent P decorated with the annotation a is written $P[a]$, and the actions it performs are also decorated with a , written $\alpha[a]$. Note that this includes τ_{then} and τ_{else} actions; in the annotated semantics, the only non-annotated action is τ . For instance, let us consider \mathcal{M}_{Π} in the annotated semantics when $\dagger_I = i$. Newly created initiator agents now appear as $\mathcal{I}\{\bar{k} \mapsto \bar{l}, \bar{n}_I \mapsto \bar{n}\}[I(\bar{l}, \bar{n})]; i \text{ new } \bar{m}. \mathcal{I}\{\bar{k} \mapsto \bar{l}, \bar{n}_I \mapsto \bar{m}\}$; they execute actions of the form $\alpha[I(\bar{l}, \bar{n})]$ with $\alpha \neq \tau$; upon termination of the agent, unannotated τ actions can be executed to create a new agent annotated $I(\bar{l}, \bar{m})$ for fresh names \bar{m} . We stress that agents having constants \bar{id}_0 as identity parameters shall be annotated with some $A(\bar{k}, \bar{n})$ where $\bar{id}_0 \subseteq \bar{k}$. Intuitively, in such a case, we keep in the annotation the information that the identity parameters \bar{id}_0 of that agent has been disclosed to the attacker.

Traces of the annotated semantics will be denoted by \mathbf{ta} . We assume² that $\bar{n}_I \neq \emptyset$ and $\bar{n}_R \neq \emptyset$, so that at any point in the execution of an annotated trace, an annotation a may not decorate more than one agent in the configuration. Thus, an annotated action may be uniquely traced back to the annotated process that performed it. We also assume that labels used to decorate output actions (*i.e.* elements of \mathcal{L}) are added to the produced output actions so that we can refer to them when needed: output actions are thus of the form $\ell : \text{out}(c, w)[a]$.

In annotated traces, τ actions are not really important. We sometimes need to reason up to these τ actions. Given two annotated trace \mathbf{ta} and \mathbf{ta}' , we write $\mathbf{ta} \stackrel{\tau}{=} \mathbf{ta}'$ when both traces together

²This assumption only serves the purpose of uniquely identifying agents, The assumed session nonces do not have to occur in the corresponding roles, so this does not require to change the protocol under study.

with their annotations are equal up to some τ actions (but not τ_{then} and τ_{else}). We write $K \xrightarrow{\text{ta}} K'$ when $K \xrightarrow{\text{ta}'} K'$ for some ta' such that $\text{ta} \stackrel{\tau}{=} \text{ta}'$.

Example 17. Considering the protocol Π_{Fh} defined in Example 8, process $\mathcal{S}_{\Pi_{\text{Fh}}}$ can notably perform the execution seen in Example 6. The annotated execution has the trace ta given below (up to some τ), where k' , n'_I and n'_R are fresh names, $a_I = I(k', n'_I)$ and $a_R = R(k', n'_R)$:

$$\begin{aligned} \text{ta} = & \ell_1 : \text{out}(c_I, w_1)[a_I].\text{in}(c_R, w_1)[a_R].\tau_{\text{then}}[a_R]. \\ & \ell_2 : \text{out}(c_R, w_2)[a_R].\text{in}(c_I, w_2)[a_I].\tau_{\text{then}}[a_I]. \\ & \ell_3 : \text{out}(c_I, w_3)[a_I].\text{in}(c_R, w_3)[a_R].\tau_{\text{then}}[a_R] \end{aligned}$$

After the initial τ actions, the annotated configuration is $(\{\mathcal{I}\sigma_I[a_I], \mathcal{R}\sigma_R[a_R], \mathcal{S}_{\Pi}\}; \emptyset)$ where $\sigma_I = \{k \mapsto k', n_I \mapsto n'_I\}$, and $\sigma_R = \{k \mapsto k', n_R \mapsto n'_R\}$. The structure is preserved for the rest of the execution with three processes in the multiset (until they become null). After ta , the annotated configuration is $(\{\mathcal{S}_{\Pi}\}; \phi_0)$ where ϕ_0 has been defined in Example 6.

Example 18. Going back to Example 15 and starting with $\mathcal{M}_{\Pi, \bar{a}}$, a possible annotated configuration obtained after some τ actions can be $K = (\mathcal{P}; \emptyset)$ where \mathcal{P} is a multiset containing:

- $P_C\{k_C \mapsto k_C^0, id_C \mapsto id_0, n_C \mapsto n_C^0, m \mapsto m_C^0\}[a_C^0]$;
- $!\text{new}(n_C, m).P_C\{k_C \mapsto k_C^0, id_C \mapsto id_0\}$;
- $P_V\{n_V \mapsto n_V^1\}[a_V^1]$; and
- $\mathcal{M}_{\Pi_{\text{DAA}}}$.

where $a_V^1 = \mathcal{I}(\epsilon, n_V^1)$ and $a_C^0 = \mathcal{R}((k_C^0, id_0), (n_C^0, m^0))$. We may note that the annotation a_V^1 contains the empty sequence ϵ since the initiator role does not rely on identity names; and the annotation a_C^0 contains id_0 .

4.2. Frame opacity

In light of attacks based on leakage from messages where non-trivial relations between outputted messages are exploited by the attacker to trace an agent, our first condition will express that all relations the attacker can establish on output messages only depend on what is already observable by him and never depend on a priori hidden information such as identity names of specific agents. Therefore, such relations cannot be exploited by the attacker to learn anything new about the agents involved in the execution. We achieve this by requiring that any reachable frame must be indistinguishable from an *idealised frame* that only depends on data already observed in the execution, and not on the specific agents (and their names) of that execution.

As a first approximation, one might take the idealisation of a frame $\{w_1 \mapsto u_1, \dots, w_l \mapsto u_n\}$ to be $\{w_1 \mapsto n_1, \dots, w_l \mapsto n_l\}$ where the n_1, \dots, n_l are distinct fresh names. It would then be very strong to require that frames obtained in arbitrary protocol executions are statically equivalent to their idealisation defined in this way. Although this would allow us to carry out our theoretical development, it would not be realistic since any protocol using, *e.g.* a pair, would fail to satisfy this condition. We thus need a notion of idealisation that retains part of the shape of messages, which a priori does not reveal anything sensitive to the attacker. We also want to allow outputs to depend on session names or previous inputs in ways that are observable, *e.g.* to cover the output of the signature of a previously inputted message.

Our idealised frames will be obtained by replacing each message, produced by an output of label ℓ , by a context that only depends on ℓ , whose holes are filled with fresh session names and (idealisations of) previously inputted messages. Intuitively, this is still enough to ensure that the attacker does not learn anything that is identity-specific. In order to formalise this notion, we assume two disjoint and countable subsets of variables: *input variables* $\mathcal{X}^i = \{x_1^i, x_2^i, \dots\} \subseteq \mathcal{X}$, and *name variables* $\mathcal{X}^n = \{x_1^n, x_2^n, \dots\} \subseteq \mathcal{X}$. We also consider a fixed but arbitrary *idealisation operator* $\text{ideal}(\cdot) : \mathcal{L} \mapsto \mathcal{T}(\Sigma, \mathcal{X}^i \cup \mathcal{X}^n)$. Variables x_j^i intuitively refers to the j -nth variable received by the agent of interest. Therefore, we assume that our idealisation operator satisfies the following: for all $\ell \in \mathcal{L}$, we have that $\text{ideal}(\ell) \cap \mathcal{X}^i \subseteq \{x_1^i, \dots, x_k^i\}$ where k is the number of inputs preceding the output labelled ℓ .

Definition 13. Let $\text{fr} : \mathcal{A} \times \mathcal{X}^n \mapsto \mathcal{N}$ be an injective function assigning names to each agent and name variable. We define the idealised frame associated to \mathbf{ta} , denoted $\Phi_{\text{ideal}}^{\text{fr}}(\mathbf{ta})$, inductively on the annotated trace \mathbf{ta} :

- $\Phi_{\text{ideal}}^{\text{fr}}(\epsilon) = \emptyset$ and $\Phi_{\text{ideal}}^{\text{fr}}(\mathbf{ta}.\alpha) = \Phi_{\text{ideal}}^{\text{fr}}(\mathbf{ta})$ if α is not an output;
- $\Phi_{\text{ideal}}^{\text{fr}}(\mathbf{ta}.\langle \ell : \text{out}(c, w)[a] \rangle) = \Phi_{\text{ideal}}^{\text{fr}}(\mathbf{ta}) \cup \{w \mapsto \text{ideal}(\ell)\sigma^i\sigma^n\}$ where
 - * $\sigma^n(x_j^n) = \text{fr}(a, x_j^n)$ when $x_j^n \in \mathcal{X}^n$, and
 - * $\sigma^i(x_j^i) = R_j\Phi_{\text{ideal}}^{\text{fr}}(\mathbf{ta})$ when $x_j^i \in \mathcal{X}^i$ and R_j is the recipe corresponding to the j -th input of agent a in \mathbf{ta} .

We may note this notion is not necessarily well-defined, as $\text{ideal}(\ell)\sigma^i\sigma^n$ may not compute to a message. Note also that well-definedness does not depend on the choice of the function fr . Remark also that, by definition, $\Phi_{\text{ideal}}^{\text{fr}}(\mathbf{ta})$ never depends on the specific identity names occurring in \mathbf{ta} . In particular, idealised frames do not depend on whether agents rely on the specific constants id_0 or not.

Example 19. Continuing Example 17, we consider the idealisation operator defined as follows: $\ell_1 \mapsto x_1^n, \ell_2 \mapsto x_2^n, \ell_3 \mapsto x_3^n$. Let fr be an injective function such that $\text{fr}(a_I, x_j^n) = n_j^I$ and $\text{fr}(a_R, x_j^n) = n_j^R$. We have that $\Phi_{\text{ideal}}^{\text{fr}}(\mathbf{ta}) = \{w_1 \mapsto n_1^I, w_2 \mapsto n_2^R, w_3 \mapsto n_3^I\}$.

On the latter simple example, such an idealisation will be sufficient to establish that any reachable frame obtained through an execution of \mathcal{M}_{PFh} is indistinguishable from its idealisation. However, as illustrated by the following two examples, we sometimes need to consider more complex idealisation operators.

Example 20. Continuing Example 9, and to have some hope to establish our indistinguishability property, namely frame opacity defined below, we need to define an idealisation operator that retains part of the shape of outputted messages. Typically, assuming that the three outputs are labelled with ℓ_1, ℓ_2 and ℓ_3 respectively, we will consider: $\ell_1 \mapsto x_1^n, \ell_2 \mapsto \langle x_2^n, x_3^n \rangle, \ell_3 \mapsto x_4^n$.

Example 21. Regarding Example 10, we need also to define an idealisation that retains the shape of the second outputted message. Moreover, the idealisation of the second outputted message will depend on the nonce previously received. Assuming that the outputs are labelled with ℓ_1 and ℓ_2 respectively, we consider: $\ell_1 \mapsto x_1^n, \ell_2 \mapsto \text{zk}(\text{sign}(\langle x_2^n, x_3^n \rangle, \text{sk}_1), x_2^n, \text{tuple}(x_1^i, x_4^n, x_5^n, \text{pk}(\text{sk}_1)))$.

The following proposition establishes that the particular choice of fr in $\Phi_{\text{ideal}}^{\text{fr}}(\mathbf{ta})$ is irrelevant with respect to static equivalence. We can thus note $\Phi_{\text{ideal}}(\mathbf{ta}) \sim \phi$ instead of there exists fr such that $\Phi_{\text{ideal}}^{\text{fr}}(\mathbf{ta}) \sim \phi$.

Proposition 1. Let $\Phi_{\text{ideal}}^{\text{fr}}(\mathbf{ta})$ (resp. $\Phi_{\text{ideal}}^{\text{fr}'}(\mathbf{ta})$) be the idealised frame associated to \mathbf{ta} relying on fr (resp. fr'). We have that $\Phi_{\text{ideal}}^{\text{fr}}(\mathbf{ta}) \sim \Phi_{\text{ideal}}^{\text{fr}'}(\mathbf{ta})$.

Proof. It is sufficient to observe that $\Phi_{\text{ideal}}^{\text{fr}}(\mathbf{ta})$ and $\Phi_{\text{ideal}}^{\text{fr}'}(\mathbf{ta})$ are equal up to a bijective renaming of names. \square

We can now formalise the notion of frame opacity as announced: it requires that all reachable frames must be statically equivalent to idealised frames.

Definition 14. The protocol Π ensures frame opacity if for any execution $(\mathcal{M}_{\Pi, \bar{id}}; \emptyset) \xrightarrow{\mathbf{ta}} (Q; \phi)$ we have that $\Phi_{\text{ideal}}(\mathbf{ta})$ is defined and $\Phi_{\text{ideal}}(\mathbf{ta}) \sim \phi$.

There are many ways to choose the idealisation operator $\text{ideal}(\cdot)$. We present below a *syntactical construction* that is sufficient to deal with almost all our case studies. This construction has been implemented as a heuristic to automatically build idealisation operators in the tool **UKano**. The tool **UKano** also provides other heuristics that generally lead to better performance but are less tight (*i.e.* they cannot always be used to establish frame opacity). We explain how **UKano** verifies frame opacity and compare the different heuristics it can leverage in Section 6.

At first reading, it is possible to skip the rest of the section and directly go to Section 4.3 since proposed canonical constructions are just instantiations of our generic notion of idealisation.

4.2.1. Syntactical idealisation

Intuitively, this construction builds the idealisation operator by examining the initiator and responder roles as syntactically given in the protocol definition. The main idea is to consider (syntactical) outputted terms one by one, and to replace identity parameters, as well as variables bound by a let construct by pairwise distinct names variables, *i.e.* variables in \mathcal{X}^n .

Definition 15. Let $\Pi = (\bar{k}, \bar{n}_I, \bar{n}_R, \dagger_I, \dagger_R, \mathcal{I}, \mathcal{R})$ be a protocol that uses input variables $\{x_1^i, x_2^i, \dots\} \subseteq \mathcal{X}^i$ (in this order) for its two roles, and distinct variables from \mathcal{X}_{let} in let constructions. Let $\sigma : \bar{k} \cup \bar{n}_R \cup \bar{n}_I \cup \mathcal{X}_{\text{let}} \rightarrow \mathcal{X}^n$ be an injective renaming. The syntactical idealisation operator maps any $\ell \in \mathcal{L}$ occurring in an output action $\ell : \text{out}(c, u)$ in \mathcal{I} or \mathcal{R} (for some c and some u) to $u\sigma$.

Example 22. Continuing Example 8, we first perform some renaming to satisfy the conditions imposed by the previous definition. We therefore replace x_1 by x_1^i in role \mathcal{I} , and y_1, y_2 by x_1^i, x_2^i in role \mathcal{R} . We assume that x_2, x_3 , and y_3 are elements of \mathcal{X}_{let} . We consider a renaming σ that maps $k, n_I, n_R, x_2, x_3, y_3$ to x_1^n, \dots, x_6^n . We obtain the following idealisation operator:

$$\ell_1 \mapsto x_2^n; \quad \ell_2 \mapsto \text{enc}(\langle x_1^i, x_3^n, x_1^n \rangle); \quad \ell_3 \mapsto \text{enc}(\langle x_5^n, x_2^n, x_1^n \rangle).$$

Considering fr as defined in Example 19, *i.e.* such that $\text{fr}(a_I, x_j^n) = n_j^I$ and $\text{fr}(a_R, x_j^n) = n_j^R$, and relying on the idealisation operator defined above, and \mathbf{ta} as given in Example 17, we have that: $\Phi_{\text{ideal}}^{\text{fr}}(\mathbf{ta}) = \{w_1 \mapsto n_2^I, w_2 \mapsto \text{enc}(\langle n_2^I, n_3^R, n_1^R \rangle), w_3 \mapsto \text{enc}(\langle n_5^I, n_2^I, n_1^I \rangle)\}$. This idealisation is different from the one described in Example 19, but it also allows us to establish frame opacity.

Example 23. Continuing Example 9, we consider a renaming σ that maps $k, n_I, n_R, x_2, x_3, y_3, r_I, r_R$ to x_1^n, \dots, x_8^n . We obtain the following idealisation operator which is also suitable to establish frame opacity:

$$\ell_1 \mapsto x_2^n; \quad \ell_2 \mapsto \langle x_3^n, \text{renc}(x_1^i, x_1^n, x_8^n) \rangle; \quad \ell_3 \mapsto \text{renc}(x_5^n, x_1^n, x_7^n)$$

Example 24. Continuing Example 10, we consider a renaming σ that maps: $k_C, id_C, n_V, n_C, m, x_2, x_3, x_4, y_3$ to $x_1^n, x_2^n, \dots, x_9^n$. We obtain the following idealisation operator:

$$\ell_1 \mapsto x_3^n; \quad \ell_2 \mapsto \text{zk}(\text{sign}(\langle x_1^n, x_2^n \rangle, \text{sk}_1), x_1^n, \text{tuple}(x_1^i, x_4^n, x_5^n, \text{pk}(\text{sk}_1))); \quad \ell_3 \mapsto \text{error}.$$

Such an idealisation operator is also suitable to establish frame opacity.

As illustrated by the previous examples, the syntactical idealisation is sufficient to conclude on most examples. Actually, using this canonical construction, we automatically build the idealisation operator and check frame opacity for all the examples we have introduced in the previous sections and for most of the case studies presented in Section 6.

4.2.2. Semantical idealisation

The previous construction is clearly purely syntactic and therefore closely connected to the way the roles of the protocol are written. Its main weakness lies in the way variables are bound by let constructions. Since there is no way to statically guess the shape of messages that will be instantiated for those variables, the previous technique replaces them by fresh session names. False negatives may result from such over-approximations. We may therefore prefer to build an idealisation operator looking at the messages outputted during a concrete execution. In such a case, we may simply retain part of the shape of messages, which a priori does not reveal anything sensitive to the attacker (*e.g.* pairs, lists). This can be formalised as follows:

Definition 16. A symbol f (of arity n) in Σ is transparent if it is a public constructor symbol that does not occur in \mathbf{E} and such that: for all $1 \leq i \leq n$, there exists a recipe $R_i \in \mathcal{T}(\Sigma_{\text{pub}}, \{w\})$ such that for any message $u = f(u_1, \dots, u_n)$, we have that $R_i\{w \mapsto u\} \Downarrow v_i$ for some v_i such that $v_i =_{\mathbf{E}} u_i$.

Example 25. Considering the signature and the equational theory introduced in Example 1 and Example 2, the symbols $\langle \rangle$ and ok are the only ones that are transparent. Regarding the pairing operator, the recipes $R_1 = \text{proj}_1(w)$ and $R_2 = \text{proj}_2(w)$ satisfy the requirements.

Once the set Σ_t of transparent functions is fixed, the idealisation associated to a label ℓ occurring in Π will be computed relying on a particular (but arbitrary) message u that has been outputted with this label ℓ during a concrete execution of \mathcal{M}_Π . The main idea is to go through transparent functions until getting stuck, and then replacing the remaining sub-terms using distinct name variables from \mathcal{X}^n .

Example 26. Considering the protocol given in Example 8, the resulting idealisation associated to Π (considering messages in ϕ_0 as defined in Example 6) is: $\ell_1 \mapsto x_1^n; \ell_2 \mapsto x_2^n; \ell_3 \mapsto x_3^n$. The protocol given in Example 9 will give us: $\ell_1 \mapsto x_1^n; \ell_2 \mapsto \langle x_2^n, x_3^n \rangle; \ell_3 \mapsto x_4^n$. Even if these idealisation operators are quite different from the ones presented in Example 22 and Example 23, they are also suitable to establish frame opacity.

In [38], the idealisation operator associated to Π was exclusively computed using this method. The technique is implemented in the tool UKano, and yields simple idealisations for which frame opacity often holds and can be established quickly. However, it happens to be insufficient to establish frame opacity in presence of function symbols that are neither transparent nor totally opaque such as signatures. Indeed, a signature function symbol is not transparent according to our definition: an attacker can make the difference between a signature $\text{sign}(m, \text{sk}(A))$ and a

random nonce. Therefore, replacing such a term by a fresh session name will never allow one to establish frame opacity. That is why we also defined other types of idealisations that produce more complex idealised messages but allow for a much better level of precision. In practice, our tool UKano has three different built-in heuristics for computing idealisations which span the range between precision (syntactical idealisation) and efficiency (semantical idealisation).

4.3. Well-authentication

Our second condition will prevent the attacker from obtaining some information about agents through the outcome of conditionals. To do so, we will essentially require that conditionals of \mathcal{I} and \mathcal{R} can only be executed successfully in honest, intended interactions. However, it is unnecessary to impose such a condition on conditionals that never leak any information, which are found in several security protocols. We characterise below a simple class of such conditionals, for which the attacker will always know the outcome of the conditional based on the past interaction.

Definition 17. A conditional $\text{let } \bar{z} = \bar{t} \text{ in } P \text{ else } Q$ occurring in $\mathcal{A} \in \{\mathcal{I}, \mathcal{R}\}$ is safe if $\bar{t} \in \mathcal{T}(\Sigma_{\text{pub}}, \{x_1, \dots, x_n\} \cup \{u_1, \dots, u_n\})$, where the x_i are the variables bound by the previous inputs of that role, and u_i are the messages used in the previous outputs of that role.

Example 27. Consider the process $\text{out}(c, u).\text{in}(c, x).\text{let } z = \text{neq}(x, u) \text{ in } P \text{ else } Q$. The conditional is used to ensure that the agent will not accept as input the message he sent at the previous step. Such a conditional is safe according to our definition.

Note that trivial conditionals required by the grammar of protocols (Definition 3) are safe and will thus not get in the way of our analysis. We can now formalise the notion of association, which expresses that two agents are having an honest, intended interaction, *i.e.* the attacker essentially did not interfere in their communications. For an annotated trace \mathbf{ta} and annotations a and a' , we denote by $\mathbf{ta}|_{a, a'}$ the subsequence of \mathbf{ta} that consists of actions of the form $\alpha[a]$ or $\alpha[a']$.

Definition 18. Given a protocol Π , two annotations $a_1 = A_1(\bar{k}_1, \bar{n}_1)$ and $a_2 = A_2(\bar{k}_2, \bar{n}_2)$ are associated in (\mathbf{ta}, ϕ) if:

- they are dual, *i.e.* $A_1 \neq A_2$, and $\bar{k}_1 = \bar{k}_2$ when $\text{fn}(\mathcal{R}) \cap \text{fn}(\mathcal{I}) \neq \emptyset$ (the shared case);
- the interaction $\mathbf{ta}|_{a_1, a_2}$ is honest for ϕ (see Definition 4).

Example 28. Continuing Example 17, $I(k', n'_I)$ and $R(k', n'_R)$ are associated in (\mathbf{ta}, ϕ_0) .

Finally, we can state our second condition.

Definition 19. The protocol Π is well-authenticating if, for any $(\mathcal{M}_{\Pi, \bar{id}}; \emptyset) \xrightarrow{\mathbf{ta}, \tau_{\text{then}}[a]} (\mathcal{P}; \phi)$ either the last action corresponds to a safe conditional, or there exists a' such that:

- (i) The annotations a and a' are associated in (\mathbf{ta}, ϕ) ;
- (ii) Moreover, when $\text{fn}(\mathcal{R}) \cap \text{fn}(\mathcal{I}) \neq \emptyset$ (the shared case), a' (resp. a) is only associated with a (resp. a') in (\mathbf{ta}, ϕ) .

Intuitively, this condition does not require anything for safe conditional as we already know that they cannot leak new information to the attacker (he already knows their outcome). For unsafe conditionals, condition (i) requires that whenever an agent a evaluates them positively (*i.e.* he does not abort the protocol), it must be the case that this agent a is so far having an

honest interaction with a dual agent a' . Indeed, as discussed in introduction, it is crucial to avoid such unsafe conditionals to be evaluated positively when the attacker is interfering because this could leak crucial information.

As illustrated in the following example, Condition (ii) is needed to prevent from having executions where an annotation is associated to several annotations, which would break unlinkability in the shared case (i.e. when $fn(\mathcal{R}) \cap fn(\mathcal{I}) \neq \emptyset$).

Example 29. We consider a protocol between an initiator and a responder that share a symmetric key k . The protocol can be described informally as follows:

1. $I \rightarrow R : \{n_I\}_k$
2. $R \rightarrow I : n_R$

Assuming that the two outputs are labelled with ℓ_1 and ℓ_2 respectively, the idealisation operator $\ell_1 \mapsto x_1^n$, $\ell_2 \mapsto x_2^n$ is suitable to establish frame opacity. We may note that the only conditional is the one performed by the responder role when receiving the ciphertext. He will check whether it is indeed an encryption with the expected key k . When an action $\tau_{\text{then}}[R(k, n_R)]$ occurs, it means that a ciphertext encrypted with k has been received by $R(k, n_R)$ and since the key k is unknown by the attacker, such a ciphertext has been sent by a participant: this is necessarily a participant executing the initiator role with key k . Hence condition (i) of well-authentication holds (and can actually be formally proved). However, condition (ii) fails to hold since two responder roles may accept a same ciphertext $\{n_I\}_k$ and therefore be associated to the same agent acting as an initiator. This correspond to an attack scenario w.r.t. our formal definition of unlinkability since such a trace will have no counterpart in \mathcal{S}_Π . More formally, the trace $\text{tr} = \text{out}(c_I, w_0). \text{in}(c_R, w_0). \tau_{\text{then}}. \text{out}(c_R, w_1). \text{in}(c_R, w_0). \tau_{\text{then}}. \text{out}(c_R, w_2)$ will be executable starting from \mathcal{M}_Π and will allow one to reach $\phi = \{w_0 \mapsto \text{enc}(n_I, k); w_1 \mapsto n_R; w_2 \mapsto n'_R\}$. Starting from \mathcal{S}_Π the second action τ_{then} will not be possible, and more importantly this will prevent the observable action $\text{out}(c_R, w_2)$ to be triggered.

While the condition (i) of well-authentication is verifiable quite easily by expressing it as simple reachability properties (as explained in Section 5.2), the required condition (ii) for the shared-case is actually harder to express in existing tools. We therefore shall prove that, for the shared case, once condition (i) of well-authentication is known to hold, condition (ii) is a consequence of two simpler conditions that are easier to verify (as shown in Section 5.2.2). First, the first conditional of the responder role should be safe — remark that if this does not hold, similar attacks as the one discussed above may break unlinkability. Second, messages labelled by some ℓ outputted in honest interactions by different agents should always be different.

Lemma 1. Let $\Pi = (\bar{k}, \bar{n}_I, \bar{n}_R, \dagger_I, \dagger_R, \mathcal{I}, \mathcal{R})$ be a protocol such that $fn(\mathcal{I}) \cap fn(\mathcal{R}) \neq \emptyset$ (shared case) that satisfies condition (i) of well-authentication. Then well-authentication holds provided that:

- (a) the first conditional that occurs in \mathcal{R} is safe;
- (b) for any execution $(\mathcal{M}_{\Pi, \bar{id}}; \emptyset) \xrightarrow{\text{ta}} (\mathcal{P}; \phi)$, if $\text{ta}_1 = \text{ta}|_{a_1, b_1}$ and $\text{ta}_2 = \text{ta}|_{a_2, b_2}$ are honest with $a_1 \neq a_2$ then for any $\ell : \text{out}(c, w_1)[a_1] \in \text{ta}_1$ and $\ell : \text{out}(c, w_2)[a_2] \in \text{ta}_2$ then $\phi(w_1) \neq_E \phi(w_2)$.

Proof. Consider an execution $\mathcal{M}_{\Pi, \bar{id}} \xrightarrow{\text{ta}, \tau_{\text{then}}[a'] } (\mathcal{P}; \phi)$ where two agents a and a' are associated and a' has performed the last τ_{then} . If this test corresponds to a safe conditional, there is nothing to prove. Otherwise, we shall prove that a is only associated to a' , and vice versa.

Agent a' is only associated to a . Consider the last input of a' (the one just before $\tau_{\text{then}}[a']$) and the output of a that occurs before this input of a' :

$$\mathcal{M}_{\Pi, \bar{id}} \xrightarrow{\text{ta.out}(c, w_\ell)[a].\text{ta}'.\text{in}(c', R)[a'].\text{ta}''.\tau_{\text{then}}[a']} (\mathcal{P}; \phi)$$

We have $R\phi \Downarrow \phi(w_\ell)$ where w_ℓ is labelled ℓ . Assume, for the sake of contradiction, that a' is associated to another agent $b \neq a$. Then, we have $R\phi \Downarrow_{=E} \phi(w'_\ell)$ for some handle, and thus thanks to Item 6 of Definition 1, we have that $\phi(w_\ell) =_E \phi(w'_\ell)$, for a handle w'_ℓ corresponding to some output of b labelled ℓ in the honest trace $\text{ta}|_{a', b}$. This contradicts assumption (b).

Agent a is only associated to a' . Agent a must have performed an input in ta : this is obvious if a is a responder, and follows from assumption (a) otherwise. Let $\ell : \text{out}(c, w_\ell)[a']$ be the output label (with annotation a') occurring in ta just before the input of a mentioned above. The considered execution is thus of the following form:

$$\mathcal{M}_{\Pi, \bar{id}} \xrightarrow{\text{ta.out}(c, w_\ell)[a'].\text{ta}'.\text{in}(c, R)[a].\text{ta}''.\tau_{\text{then}}[a']} (\mathcal{P}; \phi)$$

We know that the message m , satisfying $R\phi \Downarrow m$, which is inputted by a is equal (modulo E) to the previous output of a' , that is $\phi(w_\ell)$. As for the previous case, condition (b) implies that it cannot be equal to the output of another agent having an honest interaction in ta , thus a is only associated to a' . \square

4.4. Main result

Our main theorem establishes that the previous two conditions are sufficient to ensure unlinkability and anonymity.

Theorem 1. *Consider a protocol $\Pi = (\bar{k}, \bar{n}_I, \bar{n}_R, \dagger_I, \dagger_R, \mathcal{I}, \mathcal{R})$ and some identity names $\bar{id} \subseteq \bar{k}$. If the protocol ensures both well-authentication and frame opacity w.r.t. \bar{id} , then Π ensures unlinkability and anonymity w.r.t. \bar{id} .*

Note that, when $\bar{id} = \emptyset$, we have that $\mathcal{M}_{\Pi, \bar{id}} \approx \mathcal{M}_{\Pi}$ and our two conditions coincide on $\mathcal{M}_{\Pi, \bar{id}}$ and \mathcal{M}_{Π} . We thus have as a corollary that if \mathcal{M}_{Π} ensures well-authentication and frame opacity, then Π is unlinkable.

The proof of this theorem is detailed in Appendix A, and we explain in Section 5 how to check these two conditions in practice relying on existing verification tools. We apply our method on various case studies that are detailed in Section 6. Below, we only briefly summarize the result of the confrontation of our method to our various running examples, focusing on unlinkability.

We note \checkmark for a condition automatically checked using UKano and \times when the condition does not hold. For the analysis of Feldhofer variant with i , we do not rely on UKano (which is based on ProVerif) since ProVerif does not support the i operator. We establish the well-authentication property using Tamarin and frame opacity using ProVerif by allowing sessions to be run concurrently and thus doing a sound over-approximation of the protocol's behaviors. Frame opacity has been established relying on the syntactical idealisation as well as the semantical one, except for Example 10. Indeed, as explained at the end of Section 4.2, the semantical idealisation is not suitable in this case.

Protocol	Frame opacity	Well-authentication	Unlinkability
Feldhofer (Example 8)	✓	✓	safe
Feldhofer variant with ! (Example 14)	✓	✗	attack
Feldhofer variant with i (Example 9)	✓	✓(with Tamarin)	safe
DAA-like (Example 10)	✓	✓	safe

Fig. 3. Summary of our running examples.

5. Mechanization

We now discuss how to verify unlinkability and anonymity in practice, through the verification of our two conditions. More specifically, we describe how appropriate encodings allow one to verify frame opacity (Section 5.1) and well-authentication (Section 5.2), respectively through diff-equivalence and correspondence properties in **ProVerif**.

We additionally provide a tool, called **UKano** [45] (Section 5.3), which mechanises the encodings described in this section. Our tool takes as input a specification of a protocol in our class, computes encodings, and calls **ProVerif** to automatically check our two conditions, and thus unlinkability and anonymity. As briefly mentioned in Section 4 and detailed in Section 6, **UKano** concludes on many interesting case studies.

5.1. Frame opacity

We first explain how to check frame opacity using a slight extension³ of the diff-equivalence feature of **ProVerif** [19]. We shall start with a brief reminder on diff-equivalence in **ProVerif**, in order to describe how we extend it, before showing how this extension allows us to naturally encode frame opacity.

Diff-equivalence. Intuitively, diff-equivalence is obtained from trace equivalence by forcing the two processes (or configurations) being compared to follow the same execution. More formally, diff-equivalence is a property of *bi-processes*, which are processes (or configurations) in which some terms are replaced by *bi-terms* of the form $\text{choice}[u_1, u_2]$. Intuitively, a bi-process represents two processes: the first (resp. second) process is obtained by selecting the first (resp. second) component of choice operators. Said otherwise, each execution of a bi-process produces two frames instead of one. A bi-process is *diff-equivalent* if, when executing it, (i) both sides can always be executed synchronously (*i.e.* it never happens that a rule can be applied on one side but not on the other side) and (ii) the two resulting frames are statically equivalent.

Diff-equivalence verification in ProVerif. In order to analyze all possible runs of a bi-process, **ProVerif** relies on a modification of the Horn clause encoding that it uses for analyzing properties of single processes (*e.g.* secrecy or correspondences). Although this encoding is quite subtle and involves a lot of details, we only need here to understand its key ingredient at a high level. We present this general idea below, and refer the reader to [19] for more details. In the single-process

³Note that by leveraging other encodings first presented in [38], frame opacity can also be established using **ProVerif** off the shelf, without any extension. But those previous encodings were less general (not all idealizations were checkable) and less efficient in terms of verification time.

case, a unary predicate $\mathbf{att}(\cdot)$ is used to encode that the attacker knows some message. The attacker's capabilities are expressed as Horn clauses involving this predicate, *e.g.* the ability to encrypt is translated as

$$\forall x \forall y. \mathbf{att}(x) \wedge \mathbf{att}(y) \Rightarrow \mathbf{att}(\mathbf{enc}(x, y)).$$

Then, a process fragment of the form $\mathbf{in}(c, x). \mathbf{let } y = \mathbf{dec}(x, k) \mathbf{ in out}(c', t)$, where t is a constructor term with free variable y , is encoded as

$$\forall y. \mathbf{att}(\mathbf{enc}(y, k)) \Rightarrow \mathbf{att}(t).$$

Note that the variable x does not appear in the clause, but has been refined into $\mathbf{enc}(y, k)$ as part of the translation.

Consider now the analogue bi-process fragment

$$\mathbf{in}(c, x). \mathbf{let } y = \mathbf{dec}(x, k) \mathbf{ in out}(c', \mathbf{choice}[t_1, t_2]).$$

It corresponds to two processes, each of which may receive a message and attempt to decrypt it using k . Upon success, the processes output t_1 and t_2 respectively, relying on the value y obtained from the respective decryptions. In **ProVerif**, this bi-process would translate into the Horn clause

$$\forall y_1 \forall y_2. \mathbf{att}'(\mathbf{enc}(y_1, k), \mathbf{enc}(y_2, k)) \Rightarrow \mathbf{att}'(t'_1, t'_2)$$

where t'_1 (resp. t'_2) is t_1 (resp. t_2) in which all the occurrences of y have been replaced by y_1 (resp. y_2). This time, a binary predicate $\mathbf{att}'(\cdot, \cdot)$ is used to encode the attacker's knowledge on each side of the bi-process run: the clause roughly says that if, at some point of the execution of the bi-process, the attacker can deduce (using the same derivation) a term of the form $\mathbf{enc}(y_1, k)$ from the left frame and a term $\mathbf{enc}(y_2, k)$ from the right frame, then he will learn t_1 on the left and t_2 on the right. The attacker's capabilities are also modified to encode the effect of the attacker's capabilities on each side of the bi-process run, *e.g.* $\forall x_1 \forall x_2 \forall y_1 \forall y_2. \mathbf{att}'(x_1, x_2) \wedge \mathbf{att}'(y_1, y_2) \Rightarrow \mathbf{att}'(\mathbf{enc}(x_1, y_1), \mathbf{enc}(x_2, y_2))$ for encryption.

An extension of bi-processes. So far, the two sides of a bi-process are isolated and can be ran independently. However, the Horn clause encoding above makes it easy to lift this restriction and allow an interesting extension of the bi-process semantics. Specifically, we introduce the possibility of binding two variables at once in a bi-process input, written $\mathbf{in}(c, \mathbf{choice}[x_1, x_2]).P$. The semantics of such a construct is that x_1 is bound to the message received on the left side of the bi-process run, while x_2 is bound to the message received on the right. The crucial point is that each side of the bi-process will now have access to both x_1 and x_2 , allowing a form of communication between the two synchronous runs. Getting back to our running example, let us now consider a process fragment

$$\mathbf{in}(c, \mathbf{choice}[x_1, x_2]). \mathbf{let } y = \mathbf{dec}(x_1, k) \mathbf{ in out}(c', \mathbf{choice}[t_1, t_2])$$

where t_1 and t_2 are constructor terms with free variable y . It would be encoded as

$$\forall y_1 \forall x_2. \mathbf{att}'(\mathbf{enc}(y_1, k), x_2) \Rightarrow \mathbf{att}'(t'_1, t'_2)$$

where t'_1 (resp. t'_2) is t_1 (resp. t_2) in which all the occurrences of y have been replaced by y_1 . This time, x_2 is not refined since the bi-process does not attempt to deconstruct it, on either side. The clause expresses that if the attacker can derive a term $\text{enc}(y_1, k)$ on the left (regardless of what would be the corresponding term on the right) then he will learn t_1 on the left and t_2 on the right.

Encoding frame opacity through extended diff-equivalence. Using this extended notion of bi-process, we can now directly express frame opacity as the diff-equivalence of a bi-process. This bi-process will have $\mathcal{M}_{\Pi, \overline{id}}$ as its left process. The right process should replace each message output with its idealization, so that when the bi-process executes a trace \mathbf{ta} it results in a bi-process with a pair of frames of the form $(\Phi, \Phi_{\text{ideal}}(\mathbf{ta}))$. In itself, this can be achieved easily, as it suffices to create new names to use as values for \mathcal{X}^n variables and use appropriate input variables for the \mathcal{X}^i variables. However, in order for diff-equivalence to exactly encode frame opacity, we need to be careful about computation failures.

First, we need to ensure that tests of the real protocol, performed using **let** in the left process, are not performed on the right. Indeed, frame opacity quantifies over all execution traces of $\mathcal{M}_{\Pi, \overline{id}}$ but the tests that condition these executions are in general not going to hold for the message idealizations computed on the right of the bi-process execution. We achieve this using our extension of bi-processes by performing those tests using only left-hand side input variables. Note that it is not possible to solve this issue by pushing tests inside the **choice** $[\cdot, \cdot]$ operator in output because it is crucial that tests are performed on both sides, otherwise a disymmetric test failure would break diff-equivalence in an unwanted way. Indeed, for frame opacity, a failed test for $\mathcal{M}_{\Pi, \overline{id}}$ simply means that there is no further execution to be considered for that trace prefix.

Second, we need to ensure that computation failures that occur while computing idealizations result in a diff-equivalence failure. This is necessary to obtain a match with frame opacity, which requires that idealizations are well-defined even when destructors are involved. Hence, the computation of idealized values should be performed only on the right side of the bi-process, *i.e.* inside the **choice** $[\cdot, \cdot]$ operator in output. (Note that no computation failure can occur on the left of these **choice** $[\cdot, \cdot]$ since only constructors may be used in outputs according to our definition of protocol, *i.e.* Definition 3). Moreover, idealizations should be computed using the values of the input variables from the right side of the bi-process execution, in line with the definition of idealization, *i.e.* Definition 13.

As a result of this construction, diff-equivalence will not hold if the computation of an idealisation fails. Further, any reachable state of that bi-process will correspond to a run \mathbf{ta} of $\mathcal{M}_{\Pi, \overline{id}}$ but with a pair $(\Phi, \Phi_{\text{ideal}}(\mathbf{ta}))$ instead of Φ alone. Conversely, any run of $\mathcal{M}_{\Pi, \overline{id}}$ corresponds to a run of the bi-process, provided that the bi-process execution is not interrupted by a static inequivalence (*i.e.* $\Phi \not\sim \Phi_{\text{ideal}}(\mathbf{ta})$) or the failure to compute an idealisation. Hence, diff-equivalence of our bi-process is equivalent to frame opacity.

Let us illustrate this translation on our running example (Example 8). We first give in Figure 4 the description of the protocol in **ProVerif** syntax. This syntax is actually very close to the one we introduced in Section 2. The main difference is the fact that **ProVerif** relies on types, and here any name or variable is given the generic type bitstring. Next, we show in Figure 5 the bi-process expressing frame opacity as described above, using the syntactic idealisation (Section 4.2.1). Note that, when decrypting the first input of the initiator role, the variable \mathbf{x} is used, corresponding to the left side of the bi-process execution. The variable \mathbf{xid} , correspond to the right (idealized)

```

let I (k:bitstring) =
  new nI:bitstring;
  out(ci, nI);
  in(ci, x:bitstring);
  let (=nI, xnr:bitstring) = dec(x, k)
  in
  out(ci, enc((xnr,nI),k)).

let R (k:bitstring) =
  new nR:bitstring;
  in(cr, ynI:bitstring);
  out(cr, enc((ynI, nR), k));
  in(cr, y:bitstring);
  let (=nR,=ynI) = dec(y,k) in
  out(cr, ok).

let FH = ! new k:bitstring; ! (I(k) | R(k)).

```

Fig. 4. Our running example (Feldhofer) using ProVerif's syntax

```

let SYSTEM =
( !
  new k : bitstring;
  !
  ((
    new nI: bitstring;
    out(ci, nI);
    in(ci, choice[x,xid]: bitstring);
    let ((=nI,xnr: bitstring)) = dec(x,k) in
    new hole__xnr_I_0: bitstring;
    new hole__k_I_1: bitstring;
    out(ci, choice[enc((xnr,nI),k),enc((hole__xnr_I_0,nI),hole__k_I_1)])
  ) | (
    in(cr, choice[ynI,ynIid]: bitstring);
    new nR: bitstring;
    new hole__k_R_2: bitstring;
    out(cr, choice[enc((ynI,nR),k),enc((ynIid,nR),hole__k_R_2)]);
    in(cr, choice[y,yid]: bitstring);
    let ((=nR,=ynI)) = dec(y,k) in
    out(cr, ok)
  ))
).

```

Fig. 5. ProVerif file checking frame opacity generated by UKano (Feldhofer)

side, is not used in that case because this input is not used in idealizations. However, the variable `ynIid` corresponding to an idealized input in the responder role is used in the first output. In this example, the idealisation operator does not contain any destructor, hence the computation of the idealisation can never fail. If destructors were present, they would be computed using `let` constructs inside the right component of the `choice[·,·]` operator in output, so that their failure would not be allowed.

Practical application. Our tool `UKano` automatically constructs the bi-process described above from a description of the protocol, and calls the extension of `ProVerif` in order to check frame opacity. Until this extension is integrated in the next release of `ProVerif`, the source files of this slight extension of `ProVerif` are distributed with `UKano` [45]. Our tool does not require the user to input the idealisation function. Instead, a default idealisation is extracted from the protocol's

outputs. The user is informed about this idealisation, and if he wants to, he can bypass it using annotations or choose another heuristic to build idealisation operators. In practice, this is rarely necessary; we provide more details about this in Section 5.3. Also note that, although **ProVerif** does not support the repetition operator \mathbf{i} , we can over-approximate the behaviours of protocols using it by replacing occurrences of \mathbf{i} with $\mathbf{!}$ before checking frame opacity.

5.2. Well-authentication

We explain below how to check condition (i) of well-authentication (see Definition 19). Once that condition is established, together with frame opacity, we shall see that condition (ii) is actually a consequence of a simple assumption on the choice of idealisation, which is always guaranteed when using **UKano**. This result is established relying on the sub-conditions that have been proved to be sufficient in Lemma 1.

5.2.1. Condition (i)

Condition (i) of well-authentication is basically a conjunction of reachability properties, which can be checked in **ProVerif** using correspondence properties [3]. To each syntactical output $\mathbf{out}(c, m_0)$ of the initiator role, we associate an event, namely $\mathbf{Iout}_i(\bar{k}_I, \bar{n}_I, \bar{m}_I)$ which uniquely identifies the action. We have that:

- \bar{k}_I are the identity parameters used in the initiator role;
- \bar{n}_I are the sessions parameters; and
- \bar{m}_I are the messages inputted and outputted so far in this role including m_0 .

Such an event is placed just before the action $\mathbf{out}(c, m_0)$. We proceed similarly for each syntactical input $\mathbf{in}(c, m_0)$ putting the event $\mathbf{Iin}_i(\bar{k}_I, \bar{n}_I, \bar{m}_I)$ just after the corresponding input. Lastly, we also apply this transformation on the responder role using events of the form $\mathbf{Rout}_i(\bar{k}_R, \bar{n}_R, \bar{m}_R)$ and $\mathbf{Rin}_i(\bar{k}_R, \bar{n}_R, \bar{m}_R)$. To be able to express condition (i) relying on events, we need to consider some events that will be triggered when conditionals are passed successfully. Therefore, we add events of the form $\mathbf{Itest}_i(\bar{k}_I, \bar{n}_I, \bar{m}_I)$ (resp. $\mathbf{Rtest}_i(\bar{k}_R, \bar{n}_R, \bar{m}_R)$) at the beginning of each **then** branch of the initiator (resp. responder) role.

For each conditional of the protocol, we first check if the simple syntactical definition of *safe* conditionals holds (see Definition 17). If it is the case we do nothing for this conditional. Otherwise, we need to check condition (i) of well-authentication. This condition can be easily expressed as a correspondence property relying on the events we have introduced. Let $\bar{k}_I = (k_I^1, \dots, k_I^p)$ and $\bar{k}_R = (k_R^1, \dots, k_R^q)$. We denote $\bar{x}_I = (x_{k_I^1}, \dots, x_{k_I^p})$ and $\bar{x}_R = (x_{k_R^1}, \dots, x_{k_R^q})$. Note that when $\bar{k}_I \cap \bar{k}_R \neq \emptyset$ (shared case), we have also that $\bar{x}_I \cap \bar{x}_R \neq \emptyset$ and the correspondence property (see below) will therefore allow us to express duality of the two underlying agents.

For instance, given a conditional of the initiator role tagged with event $\mathbf{Itest}_i(\bar{k}_I, \bar{n}_I, \bar{m}_I)$, we express as a correspondence property the fact that if the conditional is positively evaluated, then the involved agent must be associated to a dual agent as follows:

1. when the event $\mathbf{Itest}_i(\bar{x}_I, \bar{y}_I, (z_1, \dots, z_\ell))$ is fired,
2. there must be a previous event $\mathbf{Iin}_i(\bar{x}_I, \bar{y}_I, (z_1, \dots, z_\ell))$ (the one just before the conditional),
3. and a previous event $\mathbf{Rout}_j(\bar{x}_R, \bar{y}_R, (z_1, \dots, z_\ell))$ (the one corresponding to the output that fed the input \mathbf{Iin}_i in an honest execution),

```

let SYSTEM = ( ! new k : bitstring; !((
  new nI:bitstring;
  event Iout_1(k,nI,nI); out(ci, nI);
  in(ci, x:bitstring); event Iin_1(k,nI,nI,x)
  let ((=nI,xnr:bitstring)) = dec(x,k) in event Itest_1(k,nI,nI,x);
  event Iout_2(k,nI,nI,x,enc((xnr,nI),k)); out(ci, enc((xnr,nI),k))
)| (
  new nR: bitstring;
  in(cr, ynI: bitstring); event Rin_1(k,nR,ynI);
  event Rout_1(k,nR,ynI,enc((ynI,nR),k)); out(cr, enc((ynI,nR),k));
  in(cr, y:bitstring); event Rin_2(k,nR,ynI,enc((ynI,nR),k),y);
  let ((=nR,=ynI)) = dec(y,k) in event Rtest_1(k,nR,ynI,enc((ynI,nR),k),y);
  event Rout_2(k,nR,ynI,enc((ynI,nR),k),y,ok); out(cr, ok)
))).

```

Fig. 6. Process modelling the Feldhofer protocol with events

```

query x:bitstring,
  y1:bitstring, y2:bitstring,
  z1:bitstring, z2:bitstring;
(event(Itest_1(x,y1,z1,z2)) ==>
(event(Iin_1(x,y1,z1,z2)) ==>
(event(Rout_1(x,y2,z1,z2)) ==>
(event(Rin_1(x,y2,z1)) ==>
(event(Iout_1(x,y1,z1))))))).

query x:bitstring, y1:bitstring,
  y2:bitstring, z1:bitstring,
  z2:bitstring, z3:bitstring;
(event(Rtest_1(x,y2,z1,z2,z3)) ==>
(event(Rin_2(x,y2,z1,z2,z3)) ==>
(event(Iout_2(x,y1,z1,z2,z3)) ==>
(event(Iin_1(x,y1,z1,z2)) ==>
(event(Rout_1(x,y2,z1,z2)) ==>
(event(Rin_1(x,y2,z1)) ==>
(event(Iout_1(x,y1,z1))))))).

```

Fig. 7. ProVerif queries for checking condition (i) on the Feldhofer protocol

4. and a previous event $\text{Rin}_j(\bar{x}_R, \bar{y}_R, (z_1, \dots, z_{\ell-1}))$ (the one just before the output Rout_j), etc.

Note that by using the same variables (z_1, \dots, z_ℓ) in both the initiator and responder roles, we express that the messages that are outputted and inputted are equal modulo the equational theory E . We provide in Figure 6 the process obtained by applying the transformation on the Feldhofer protocol (Example 8). In Figure 7, we show the ProVerif queries we have to consider to check condition (i) on the two conditionals.

Some practical considerations. In our tool, safe conditionals are not automatically identified. Actually, the tool lists all conditionals and tells which ones satisfy condition (i) of well-authentication. The user can thus easily get rid of the conditionals that he identifies as safe. Furthermore, the structure of the ProVerif file produced by UKano makes it easy for the user to remove the proof obligations corresponding to safe conditionals. To obtain more precise encodings once the translation in Horn clauses is performed by ProVerif, we sometimes push the creation of session parameters (i.e. instructions of the form `new nI`). Therefore, in order to ensure the existence of at least one session parameter in each event, we systematically introduce a fresh session parameter `sessI` (resp. `sessR`) which is generated at the beginning of the initiator (resp. responder) role. Such parameters are systematically added in the events, and since they

do not occur in the messages exchanged during the protocol execution, there is no need to push them.

Note that, for some examples, we also verified condition (i) of well-authentication using **Tamarin** by encoding the queries described above as simple lemmas. In our case, one of the most important advantage of **Tamarin** over **ProVerif** is its capability to model the repetition operator i and thus protocols for which a role executes its sessions in sequence. Relying on **Tamarin**, we were thus able to verify condition (i) for protocols that ensure unlinkability when sessions are running sequentially but not when they are running concurrently, *e.g.* we automatically verified the variant of Feldhofer described in Example 9.

5.2.2. Condition (ii) - shared case

To verify Condition (ii) of well-authentication, we rely on Lemma 1 which provide two sufficient sub-conditions. Condition (a) of Lemma 1 can be checked manually; **UKano** leaves it to the user. Condition (b) may in general be very difficult to verify. While it is surely possible to reduce the verification of this sub-condition to classical reachability properties verifiable in **ProVerif**, we prefer to give a more direct verification technique.

Indeed, once frame opacity is known to hold, condition (b) actually follows immediately from simple properties of the idealisation function, since checking that honest outputs cannot be confused in executions of $\mathcal{M}_{\Pi, \bar{id}}$ is equivalent to checking that they cannot be confused in idealised executions. Often, the idealisation function uses only function symbols that do not occur in \mathbf{E} and such that at least one session variable $x^n \in \mathcal{X}^n$ occurs in $\text{ideal}(\ell)$ for each honest output label ℓ . Checking that the idealisation function enjoys these properties is straightforward. Let us now show that it implies condition (b) of Lemma 1.

Proposition 2. *Let $\Pi = (\bar{k}, \bar{n}_I, \bar{n}_R, \dagger_I, \dagger_R, \mathcal{I}, \mathcal{R})$ be a protocol such that $\text{fn}(\mathcal{I}) \cap \text{fn}(\mathcal{R}) \neq \emptyset$ (shared case). Consider an idealisation operator $\text{ideal}(\cdot)$ such that, for any label $\ell \in \mathcal{L}$ occurring in the honest execution of Π , some name variable $x \in \mathcal{X}^n$ appears in $\text{ideal}(\ell)$ in a position only under symbols $\mathbf{f} \in \Sigma_c$ that do not occur in equations of \mathbf{E} . If Π satisfies frame opacity for the idealised operator $\text{ideal}(\cdot)$ then condition (b) of Lemma 1 holds.*

Proof. Consider an execution \mathbf{ta} of $\mathcal{M}_{\Pi, \bar{id}}$ where agent a_1 performs an output with label ℓ and handle w_1 , and agent $a_2 \neq a_1$ performs another output with label ℓ and handle w_2 . We assume that ℓ occurs in the honest execution of Π and we note ϕ the resulting frame from the above execution. Assume, for the sake of contradiction, that $\phi(w_1) =_{\mathbf{E}} \phi(w_2)$. Since the protocol ensures frame opacity for the idealised operator $\text{ideal}(\cdot)$, we deduce that $\Phi_{\text{ideal}}^{\text{fr}}(\mathbf{ta})(w_1) =_{\mathbf{E}} \Phi_{\text{ideal}}^{\text{fr}}(\mathbf{ta})(w_2)$. By hypothesis, some name variable $x_1 \in \mathcal{X}^n$ occurs in $\text{ideal}(\ell)$ in a position which (even after a substitution) cannot be erased by the equational theory nor the computation relation. In other words we have that $\text{fr}(a_1, x^n)$ occurs in $\Phi_{\text{ideal}}^{\text{fr}}(\mathbf{ta})(w_1)$, and similarly $\text{fr}(a_2, x^n)$ occurs in $\Phi_{\text{ideal}}^{\text{fr}}(\mathbf{ta})(w_2)$, at the same position under non-malleable constructor symbols only. Since we have assumed (in Section 2.1) that our equational theory is non-degenerate, this implies that $\text{fr}(a_1, x^n) =_{\mathbf{E}} \text{fr}(a_2, x^n)$ and contradicts the injectivity of fr . \square

5.3. The tool UKano

As mentioned earlier, the tool **UKano** [45] automatizes the encodings described in this section. It takes as input a **ProVerif** model specifying the protocol to be verified (and the identity names \bar{id}) and returns:

1. whether frame opacity could be established or not: in particular, it infers an idealisation operator that, when in the shared case, satisfies the assumptions of Proposition 2;
2. and the list of conditionals for which condition (i) of well-authentication holds.

If frame opacity holds and condition (i) of well-authentication holds for all conditionals — possibly with some exceptions for conditionals the user can identify as safe — then the tool concludes that the protocol given as input ensures unlinkability and anonymity w.r.t. \overline{id} . Note that the tool detects whether $fn(\mathcal{I}) \cap fn(\mathcal{R}) = \emptyset$ or not and adapts the queries for verifying item (i) of well-authentication accordingly. Our tool uses heuristics to build idealised operators that always satisfy the assumptions of Proposition 2). Actually, three different heuristics have been implemented.

Syntactic heuristic. The syntactic heuristic fully adopts the canonical syntactical construction from Section 4.2 (and displays a warning message when in the shared case since all requirements are not met in this case). It can be enabled using the option `-ideal-syntactic`.

Semantic heuristic. The semantic heuristic (enabled with the option `-ideal-semantic`) follows the semantical construction from Section 4.2 with only tuples identified as transparent. Roughly, idealisation of a tuple is a tuple of idealisations of the corresponding sub-terms and idealisation of any other term is a fresh session variable in \mathcal{X}^n . Such an idealised operator is much less precise (*i.e.* may lead to more false negatives) but since idealised messages are much simpler, it allows better performance when it works.

Quasi-syntactic heuristic. This heuristic follows the canonical syntactical construction described in Section 4.2 except that sub-terms having a function symbol at top-level that is involved in the equational theory will be replaced by a fresh session name in order to comply with hypothesis of Proposition 2. This is the default heuristic in UKano.

Finally, the user can also define its own idealisations and the tool UKano will check that assumptions of Proposition 2 are satisfied when in the shared case.

At a technical level, we built UKano on top of ProVerif. We only re-used the lexer, parser and AST of ProVerif and build upon those a generator and translator of ProVerif models implementing our sufficient conditions via the above encodings. This effort represents about 2k OCaml LoC. The official page of the tool UKano with distributed releases of the tool can be found at <http://projects.lsv.ens-cachan.fr/ukano/>. We also distribute ProVerif v1.97 modified for handling extended diff-equivalence (see Section 5.1). The difference between our modified version of ProVerif v1.97 and the original one is about 60 lines of code.

6. Case studies

In this section we apply our verification method to several case studies. We rely on our tool UKano to check whether the protocol under study satisfies frame opacity and well-authentication as defined in Section 4. We also discuss some variations of the protocols to examine how privacy is affected. Remind that if privacy can be established for concurrent sessions (*i.e.* $\dagger_I = \dagger_R =!$) then it implies privacy for all other scenarios as well, *i.e.* when $\dagger_I, \dagger_R \in \{!, !\}$. We thus model protocols with concurrent sessions and discuss alternative scenarios only when attacks are found. The source code of our tool and material to reproduce results can be found at

<http://projects.lsv.ens-cachan.fr/ukano/>.

All case studies discussed in this section except two (*i.e.* DAA in Section 6.4 and ABCDH in Section 6.5) have been automatically verified using our tool UKano without any manual effort. We discuss little manual efforts needed to conclude for DAA and ABCDH in the dedicated sections. We used UKano v0.3 based on ProVerif v1.97 on a computer with following specifications:

- OS: Linux 3.10-2-amd64 #1 SMP Debian 3.10.5-1x86_64 GNU/Linux
- CPU / RAM: Intel(R) Xeon(R) CPU X5650 @ 2.67GHz / 47GO

6.1. Hash-Lock protocol

We consider the Hash-Lock protocol as described in [39]. This is an RFID protocol that has been designed to achieve privacy even if no formal proof is given. We suppose that initially, each tag has his own key k and the reader maintains a database containing those keys. The protocol relies on a hash function, denoted h , and can be informally described as follows.

$$\begin{aligned} \text{Reader} \rightarrow \text{Tag} &: n_R \\ \text{Tag} \rightarrow \text{Reader} &: n_T, h(n_R, n_T, k) \end{aligned}$$

This protocol falls into our generic class of 2-party protocols in the shared case, and frame opacity and well-authentication can be automatically established in less than 0.01 second. We can therefore conclude that the protocol preserves unlinkability (note that anonymity does not make sense here). Actually, all implemented heuristics were able to successfully establish frame opacity automatically.

6.2. LAK protocol

We present an RFID protocol first introduced in [40], and we refer to the description given in [46]. To avoid traceability attacks, the main idea is to ask the tag to generate a nonce and to use it to send a different message at each session. We suppose that initially, each tag has his own key k and the reader maintains a database containing those keys. The protocol is informally described below (h models a hash function). In the original version (see *e.g.* [46]), in case of a successful execution, both parties update the key k with $h(k)$ (they always store the last two keys). Our framework does not allow one to model protocols that rely on a mutable state. Therefore, we consider here a version where the key is not updated at the end of a successful execution allowing the key k to be reused from one session to another. This protocol lies in the shared case since the identity name k is used by the reader and the tag.

$$\begin{aligned} \text{Reader} \rightarrow \text{Tag} &: r_1 \\ \text{Tag} \rightarrow \text{Reader} &: r_2, h(r_1 \oplus r_2 \oplus k) \\ \text{Reader} \rightarrow \text{Tag} &: h(h(r_1 \oplus r_2 \oplus k) \oplus k \oplus r_1) \end{aligned}$$

Actually, this protocol suffers from an authentication attack. The protocol does not allow the reader to authenticate the tag. This attack can be informally described as follows (and already exists on the original version of this protocol). By using algebraic properties of \oplus , an attacker

can impersonate a tag by injecting previously eavesdropped messages. Below, $I(A)$ means that the attacker plays the role A .

$$\begin{aligned}
I(\text{Reader}) \rightarrow \text{Tag} &: r_1 \\
\text{Tag} \rightarrow \text{Reader} &: r_2, h(r_1 \oplus r_2 \oplus k) \\
\text{Reader} \rightarrow \text{Tag} &: r'_1 \\
I(\text{Tag}) \rightarrow \text{Reader} &: r_2^I, h(r_1 \oplus r_2 \oplus k) \\
\text{Reader} \rightarrow \text{Tag} &: h(h(r_1 \oplus r_2 \oplus k) \oplus k \oplus r'_1)
\end{aligned}$$

where $r_2^I = r'_1 \oplus r_1 \oplus r_2$, thus $h(r_1 \oplus r_2 \oplus k) =_{\text{E}} h(r'_1 \oplus r_2^I \oplus k)$.

Due to this, the protocol does not satisfy our well-authentication requirement even with sessions in sequence for **Tag** and **Reader**. Indeed, the reader can end a session with a tag whereas the tag has not really participated to this session. In other words, the reader passes a test (which does not correspond to a safe conditional) with success, and therefore performs a τ_{then} action whereas it has not interacted honestly with a tag. Actually, this trace can be turned into an attack against the unlinkability property (for any combination of $\dagger_I, \dagger_R \in \{!, !\}$). Indeed, by continuing the previous trace, the reader can send a new request to the tag generating a fresh nonce r'_1 . The attacker $I(\text{Tag})$ can again answer to this new request choosing his nonce r_2'' accordingly, *i.e.* $r_2'' = r'_1 \oplus r_1 \oplus r_2$. This execution, involving two sessions of the reader talking to the same tag, cannot be mimicked in the single session scenario, and corresponds to an attack trace.

More importantly, this scenario can be seen as a traceability attack on the stateful version of the protocol leading to a practical attack. The attacker will first start a session with the targeted tag by sending it a nonce r_1 and storing its answer. Then, later on, he will interact with the reader as described in the second part of the attack scenario. Two situations may occur: either the interaction is successful meaning that the targeted tag has not been used since its last interaction with the attacker; or the interaction fails meaning that the key has been updated on the reader's side, and thus the targeted tag has performed a session with the reader since its last interaction with the attacker. This attack shows that the reader may be the source of leaks exploited by the attacker to trace a tag. This is why we advocate for the strong notion of unlinkability we used, taking into account the reader and considering it as important as the tag.

We may note that the same protocol was declared untraceable in [46] due to the fact that they have in mind a weaker notion of unlinkability. Actually, their notion captures the intuitive notion that a tag is untraceable if for any execution in which two actions are performed by the same tag, there is another execution indistinguishable from the original one in which the actions have been performed by two different tags. We may note that in the attack scenario described above, the tag in itself does not leak anything but the reader does, explaining why this weak notion of untraceability missed this attack.

Now, to avoid the algebraic attack due to the properties of the xor operator, we may replace it by the pairing operator. The resulting protocol is a 2-party protocol that falls into our class, and for which frame opacity and well-authentication can be established (with concurrent sessions) using **UKano** (any heuristic is suitable for that). Therefore, Theorem 1 allows us to conclude that it preserves unlinkability.

$$\begin{aligned}
T(k_E, k_M) = & \text{new } n_T. \text{new } k_T. \text{out}(c_T, n_T). \text{in}(c_T, x). \\
& \text{let } x_E = \text{proj}_1(x), x_M = \text{proj}_2(x), z_{\text{test}} = \text{eq}(x_M, \text{mac}(x_E, k_M)) \text{ in} \\
& \quad \text{let } z'_{\text{test}} = \text{eq}(n_T, \text{proj}_1(\text{proj}_2(\text{dec}(x_E, k_E)))) \text{ in } \text{out}(c_T, \langle m, \text{mac}(m, k_M) \rangle) \\
& \quad \text{else } \text{out}(\text{error}_{\text{Nonce}}) \\
& \text{else } \text{out}(\text{error}_{\text{Mac}}) \\
& \text{where } m = \text{enc}(\langle n_T, \langle \text{proj}_1(\text{dec}(x_E, k_E)), k_T \rangle \rangle, k_E).
\end{aligned}$$

Fig. 8. Description of the passport's role

6.3. BAC protocol and some others

An e-passport is a paper passport with an RFID chip that stores the critical information printed on the passport. The International Civil Aviation Organization (ICAO) standard [1] specifies several protocols through which this information can be accessed. Before executing the Basic Access Control (BAC) protocol, the reader optically scans a weak secret from which it derives two keys k_E and k_M that are then shared between the passport and the reader. Then, the BAC protocol establishes a key seed from which two sessions keys are derived. The session keys are then used to prevent skimming and eavesdropping on subsequent communications.

In [7], two variants of the BAC protocol are described and analysed. We refer below to these two variants as the French version and the United Kingdom (U.K.) version. The U.K. version is claimed unlinkable (with no formal proof) whereas an attack is reported on the French version. We first give an informal description of the BAC protocol using Alice & Bob notation:

$$\begin{aligned}
& \text{Tag} \rightarrow \text{Reader} : n_T \\
& \text{Reader} \rightarrow \text{Tag} : \{n_R, n_T, k_R\}_{k_E}, \text{mac}_{k_M}(\{n_R, n_T, k_R\}_{k_E}) \\
& \text{Tag} \rightarrow \text{Reader} : \{n_T, n_R, k_T\}_{k_E}, \text{mac}_{k_M}(\{n_T, n_R, k_T\}_{k_E})
\end{aligned}$$

Then, to explain the difference between the two versions, we give a description of the passport's role in Figure 8. We do not model the `getChallenge` constant message that is used to initiate the protocol but it is clear this message does not play any role regarding the security of the protocol. We consider the signature given in Example 1 augmented with a function symbol `mac` of arity 2. This is a public constructor whose purpose is to model message authentication code, taking as arguments the message to authenticate and the mac key. There is no rewriting rule and no equation regarding this symbol. We also assume public constants to model error messages. The U.K. version of the protocol does not distinguish the two cases of failure, *i.e.* `errorMac` and `errorNonce` are the same constant, whereas the French version does. The relevant point is the fact that, in case of failure, the French version sends a different error message indicating whether the failure occurs due to a problem when checking the mac, or when checking the nonce. This allows the attacker to exploit this conditional to learn if the mac key of a tag is the one used in a given message $\langle m, \text{mac}(m, k) \rangle$. Using this, he can very easily trace a tag T by first eavesdropping an honest interaction between the tag T and a reader.

The U.K. version of the BAC protocol is a 2-party protocol according to our definition. Note that since the two error messages are actually identical, we can merge the two `let` instructions, and therefore satisfy our definition of being a responder role. Then, we automatically proved

frame opacity and well-authentication using **UKano**. It took less than 0.1 second independently of the chosen heuristic regarding frame opacity. Therefore, Theorem 1 allows us to conclude that unlinkability is indeed satisfied.

Regarding the French version of this protocol, it happens that the passport's role is neither an initiator role, nor a responder role according to our formal definition. Indeed, our definition of a role, and therefore of a 2-party protocol does not allow to model two sequences of tests that will output different error messages in case of failure. As illustrated by the attack on the French version of the BAC protocol, imposing this syntactic condition is actually a good design principle w.r.t. unlinkability.

Once the BAC protocol has been successfully executed, the reader gains access to the information stored in the RFID tag through the Passive and Active Authentication protocols (PA and AA). They are respectively used to prove authenticity of the stored information and prevent cloning attacks, and may be executed in any order. A formal description of these protocols is available in [6]. These two protocols also fall into our class and our conditions can be checked automatically both for unlinkability and anonymity properties. We can also use our technique to analyse directly the three protocols together (*i.e.* the U.K. version of the BAC together with the PA and AA protocols in any order). We analysed both orders, *i.e.* BAC followed by PA, and then AA, as well as BAC following by AA, and then AA) We establish unlinkability and anonymity w.r.t. all private data stored in the RFID chip (name, picture, etc.). **UKano** concludes within 1 second to establish both well-authentication and frame opacity (independently of the selected heuristic).

6.4. PACE protocol

The Password Authenticated Connection Establishment protocol (PACE) has been proposed by the German Federal Office for Information Security (BSI) to replace the BAC protocol. It has been studied in the literature [17], [16], [26] but to the best of our knowledge, no formal proofs about privacy have been given. Similarly to BAC, its purpose is to establish a secure channel based on an optically-scanned key k . This is done in four main steps (see Figure 9):

- The tag chooses a random number s_T , encrypts it with the symmetric key k shared between the tag and the reader and sends the encrypted random number to the reader (message 1).
- Both the tag and the reader perform a Diffie-Hellman exchange (messages 2 & 3), and derive G from s_T and $g^{n_R n_T}$.
- The tag and the reader perform a Diffie-Hellman exchange based on the parameter G computed at the previous step (messages 5 & 6).
- The tag and the reader derive a session key k' which is confirmed by exchanging and checking the authentication tokens (messages 8 & 9).

Moreover, at step 6, the reader is not supposed to accept as input a message which is equal to the previous message that it has just sent.

To formalise such a protocol, we consider $\Sigma_c = \{\text{enc}, \text{dec}, \text{dh}, \text{mac}, \text{gen}, \text{g}, \text{ok}\}$, and $\Sigma_d = \{\text{neq}\}$. Except g and ok which are public constants, all these function symbols are public constructor symbols of arity 2. The destructor neq has already be defined in Example 3. The symbol dh is used to model modular exponentiation whereas mac will be used to model message authentication

1. Tag \rightarrow Reader : $\{s_T\}_k$
2. Reader \rightarrow Tag : g^{n_R}
3. Tag \rightarrow Reader : g^{n_T}
4. Both parties compute $G = \text{gen}(s_T, g^{n_R n_T})$.
5. Reader \rightarrow Tag : $G^{m'_R}$
6. Tag \rightarrow Reader : $G^{m'_T}$
7. Both parties compute $k' = G^{m'_R m'_T}$
8. Reader \rightarrow Tag : $\text{mac}(G^{m'_T}, k')$
9. Tag \rightarrow Reader : $\text{mac}(G^{m'_R}, k')$

Fig. 9. PACE in Alice & Bob notation

$$\begin{aligned} \mathcal{R}_{\text{PACE}} := & \text{in}(c_R, y_1). \\ & \text{out}(c_R, \text{dh}(g, n_R)).\text{in}(c_R, y_2). \\ & \text{out}(c_R, \text{dh}(G, n'_R)).\text{in}(c_R, y_3). \\ & \text{let } y_{\text{test}} = \text{neq}(y_3, \text{dh}(G, n'_R)) \text{ in} \\ & \quad \text{out}(c_R, \text{mac}(y_3, k')); \\ & \quad \text{in}(c_R, y_4). \\ & \quad \text{let } y_5 = \text{eq}(y_4, \text{mac}(\text{dh}(G, n'_R), k')) \text{ in } R'. \end{aligned}$$

where $G = \text{gen}(\text{dec}(y_1, k), \text{dh}(y_2, n_R))$ and $k' = \text{dh}(y_3, n'_R)$.

Fig. 10. Process $\mathcal{R}_{\text{PACE}}$

code. We consider the equational theory \mathbf{E} defined by the following equations:

$$\text{dec}(\text{enc}(x, y), y) = x \quad \text{dh}(\text{dh}(x, y), z) = \text{dh}(\text{dh}(x, z), y)$$

We consider the process $\mathcal{R}_{\text{PACE}}$ as described in Figure 10. We do not detail the continuation R' and we omit trivial conditionals. The process modelling the role $\mathcal{I}_{\text{PACE}}$ can be obtained in a similar way. Then, we consider $\Pi_{\text{PACE}} = (k, (s_T, n_T, n'_T), (n_R, n'_R), !, !, \mathcal{I}_{\text{PACE}}, \mathcal{R}_{\text{PACE}})$ which falls into our generic class of 2-party protocols. Unfortunately, **ProVerif** cannot handle the equation above on the dh operator (due to some termination issues). Instead of that single equation, we consider the following equational theory that is more suitable for **ProVerif**:

$$\text{dh}(\text{dh}(g, y), z) = \text{dh}(\text{dh}(g, z), y) \quad \text{dh}(\text{dh}(\text{gen}(x_1, x_2), y), z) = \text{dh}(\text{dh}(\text{gen}(x_1, x_2), z), y)$$

This is sufficient for the protocol to work properly but it obviously lacks equations that the attacker may exploit.

First, we would like to highlight an imprecision in the official specification that may lead to practical attacks on unlinkability. As the specification seems to not forbid it, we could have assumed that the decryption operation in $G = \text{gen}(\text{dec}(y_1, k), \text{dh}(y_2, n_R))$ is implemented in such a way that it may fail when the key k does not match with the key of the ciphertext y_1 . In that case, an attacker could eavesdrop a first message $c^0 = \text{enc}(s_T^0, k^0)$ of a certain tag T^0 and then, in a future session, it would let the reader optically scan a tag T but replace its challenge $\text{enc}(s_T, k)$ by c^0 and wait for an answer of the reader. If it answers, he learns that the decryption did not

fail and thus $k = k^0$: the tag T is actually T^0 . We discovered this attack using our method since, in our first attempt to model the protocol, we modelled $\mathbf{dec}(\cdot, \cdot)$ as a destructor (that may fail) and the computation of G as an evaluation:

$$\text{let } G = \text{gen}(\mathbf{dec}(y_1, k), \text{dh}(y_2, n_R)) \text{ in } [\dots]$$

In order to declare the protocol well-authenticating, this conditional computing G which is not safe has to satisfy our requirement (see Definition 19). However, as witnessed by the attack scenario described above (the reflection attack), the condition actually fails to hold. Incidentally, the same attack scenario shows that the protocol does not ensure unlinkability (this scenario cannot be observed when interacting with \mathcal{S}_{Π}). Similarly to the attack on LAK, we highlight here the importance to take the reader into account and give it as much importance as the tag in the definition of unlinkability. Indeed, it is actually a leakage from the reader that allows an attacker to trace a specific tag.

Second, we now consider that decryption is a constructor, and thus cannot fail, and we report on an attack that we discovered using our method on some models of PACE found in the literature [17],[16],[26]. Indeed, in all those papers, the first conditional of the reader

$$\text{let } y_{\text{test}} = \text{neq}(y_3, \text{dh}(G, n'_R)) \text{ in}$$

is omitted. Then the resulting protocol is not well-authenticating. To see this, we simply have to consider a scenario where the attacker will send to the reader the message it has outputted at the previous step. Such an execution will allow the reader to execute its role until the end, and therefore execute τ_{then} , but the resulting trace is not an honest one. Again, this scenario can be turned into an attack against unlinkability as explained next. As before, an attacker could eavesdrop a first message $c^0 = \mathbf{enc}(s_T, k^0)$ of a certain tag T^0 . Then, in a future session, it would let the reader optically scan a tag T but replace its challenge $\mathbf{enc}(s_T, k)$ by c^0 . Independently of whether k is equal to k^0 or not, the reader answers g^{n_R} . The attacker then plays the two rounds of Diffie-Hellman by reusing messages from the reader (he actually performs a reflection attack). More precisely, he replies with $g^{n_T} = g^{n_R}$, $G^{n'_T} = G^{n'_R}$ and $\mathbf{mac}(G^{n'_R}, k') = \mathbf{mac}(G^{n'_T}, k')$. The crucial point is that the attacker did not prove he knows k (whereas he is supposed to do so to generate G at step 4) thanks to the reflection attack that is not detected. Now, the attacker waits for the reader's answer. If it is positive (the process R' is executed), he learns that $k = k^0$: the tag T is actually the same as T^0 .

Third, we turn to PACE as properly understood from the official specification: when the latter test is present and the decryption may not fail. In that case, we report on a new attack. UKano found that the last test of the reader violates well-authentication. This is the case for the following scenario: the message $\mathbf{enc}(s_T, k)$ sent by a tag $T(k, n_T)$ is fed to two readers $R(k, n_R^1), R(k, n_R^2)$ of same identity name. Then, the attacker just forwards messages from one reader to the other. They can thus complete the two rounds of Diffie-Hellman (note that the test avoiding reflection attacks holds). More importantly, the mac-key verification phase (messages 8 and 9 from Figure 9) goes well and the attacker observes that the last conditional of the two readers holds. This violates well-authentication but also unlinkability because the latter scenario cannot be observed at all in \mathcal{S}_{Π} : if the attacker makes two readers talk to each other in \mathcal{S}_{Π} they

cannot complete a session because they must have different identity names. In practice, this flaw seems hard to exploit but it could be a real privacy concern: if a tag initiates multiple readers, an attacker may learn which ones it had initiated by forwarding messages from one to another. It does not seem to be realistic in the e-passport scenario, but could be harmful in other contexts. It seems that, in the e-passport context, a modelling with sequential sessions would be more realistic. We come back to such a modelling at the end of this section.

Further, we propose a simple fix to the above attack by adding tags avoiding confusions between reader's messages and tag's messages. It suffices to replace messages 8 and 9 from Figure 9 by respectively $\text{mac}(\langle c_r, G^{n_T} \rangle, k')$ and $\text{mac}(\langle c_t, G^{n_R} \rangle, k')$ where c_r, c_t are public constants, and adding the corresponding checks. Well-authentication can be automatically established using UKano in around 1 minute. Frame opacity can be automatically established using any heuristic described in Section 5.3. Heuristics producing more complex idealisations (*i.e.* the syntactic one) are less efficient. Nevertheless, the tool concludes in at most 16 seconds. We thus conclude that PACE with tags preserves unlinkability in the model considered here.

Finally, one could argue that executing sessions concurrently does not seem practical. Indeed, e-passports RFID chips' content are assumed to be impossible to clone. It is thus expected that there exists at most one physical e-passport equipped with given identity names. Therefore, we have investigated the scenario where sessions can be executed only sequentially. We have turned to Tamarin since ProVerif is not able to model faithfully such scenarios. We wrote a Tamarin model encoding well-authentication and found that this condition does not hold even with the tagged version. This contrasts with the positive result obtained with ProVerif. Actually, this comes from the fact that Tamarin models Diffie-Hellman exponentiation in a more faithful way than ProVerif. Some behaviours that were not possible in the ProVerif model become possible, and it happens that well-authentication is not satisfied in such a model. Indeed, the attacker can alter the Diffie-Hellman shares, as informally depicted in Figure 11, without impacting successive agents' conditionals. This is problematic because successful tests will pass (independently of the

1. Tag \rightarrow Reader : $\{s_T\}_k$
2. Reader \rightarrow Attacker : g^{n_R}
- 2'. Attacker \rightarrow Tag : $(g^{n_R})^X$
3. Tag \rightarrow Attacker : g^{n_T}
- 3'. Attacker \rightarrow Reader : $(g^{n_T})^X$

Fig. 11. Example of successful but dishonest interaction (X can be any message)

message X) while such interactions are not honest according to our current definition of honest trace (see Definition 4). This problematic interaction is however not detected in ProVerif, due to the lack of equations in the underlying equational theory: the final keys computed by both parties will be different, $((g^{n_R})^X)^{n_T}$ for the tag and $((g^{n_T})^X)^{n_R}$ for the reader. Therefore such an interaction can not be completed successfully, and well-authentication will be established.

We have ideas to tackle this issue. First, one could extend the notion of "honest trace associated to a protocol" (Definition 5) as follows: to any protocol, we associate a set of symbolic traces that are roughly traces with (possibly) variables in recipes. For instance, for PACE, one may use $\text{tr}_h = \text{out}(c_I, w_1).\text{in}(c_R, \text{dh}(w_1, X)).\text{out}(c_R, w_2).\text{in}(c_I, \text{dh}(w_2, X)) \dots$ in addition to the standard non-symbolic trace. However, in order to adapt our proof technique, we need to make sure that

whatever the recipes chosen to fill in the variables (*e.g.* X in tr_h), the resulting concrete trace can be executed by the protocol and the produced frame has always the same idealisation. Remark that this is the case for tr_h in the case of the PACE protocol. We hope that our theorem and our method could be adapted in this way in order to deal with PACE and other examples based on such Diffie-Hellman exchanges, but we leave this task as future work.

6.5. Attributed-based authentication scenario using ABCDH protocol

Most authentication protocols are identity-based: the user needs to provide his identity and prove to the service provider he is not trying to impersonate somebody else. However, in many contexts, the service provider just needs to know that the user has some non-identifying attributes (*e.g.* age, gender, country, membership). For instance, a liquor shop just needs to have the proof that the user has the right to buy liquors (*i.e.* that he is old enough) and does not need to know the full identity of the user (*e.g.* as it is currently done when showing ID cards). Attribute-based authentication protocols solve this problem and allow a user to prove to another user, within a secure channel, that he has some attributes without disclosing its identity.

We used our method to automatically establish unlinkability of a typical use case of such a protocol taking part to the IRMA project⁴. We analysed a use case of the protocol ABCDH as defined in [5]. This protocol allows a smartcard C to prove to some Verifier V that he has the required attributes. The protocol aims at fulfilling this goal without revealing the identity of C to V or to anyone else. One of its goal is also to avoid that any other smartcard C' replays those attributes later on. The protocol should also ensure unlinkability of C . To the best of our knowledge, there was no prior formal analysis of that security property for this protocol.

The key ingredient of this protocol is *attribute-based credential* (ABC). It is a cryptographic container for attributes. In ABC, attributes are signed by some issuers and allow for *selective disclosure* (SD): it is possible to produce a zero-knowledge (ZK) proof revealing a subset of attributes signed by the issuer along with a proof that the selected disclosed attributes are actually in the credential. This non-interactive proof protocol can be bound to some fresh data to avoid replay attacks. We shall use the notation $\text{SD}(\bar{a}_i; n)$ to denote the selective disclosure of attributes \bar{a}_i bound to n . Note that $\text{SD}(\emptyset; n)$ (no attribute is disclosed) still proves the existence of a credential. There are two majors ABC schemes: Microsoft U-Prove [42] and IBM's Idemix [24]. We decided to model IBM's scheme (since it is the one that is used in IRMA) following the formal model given in [25]. We may note that we consider here some privacy issues whereas the security analysis presented in [25] is dedicated to the analysis of some reachability properties. It involves complex cryptographic primitives (*e.g.* commitments, blind signature, ZK proofs) but ProVerif can deal with them all. In this scheme, each user has a master secret never revealed to other parties. Issuers issue credentials bound to the master secret of users (note that users are known to issuers under pseudonyms). A SD consists in a ZK proof bound to n proving some knowledge: knowledge of the master secret, knowledge of a credential bound to the master secret, knowledge that the credential has been signed by the given organisation, knowledge that the credential contains some given attributes.

We analyse the ABCDH [5] using the model of SD from [25] used in the following scenario:

- an organisation O_{age} issues credentials about the age of majority;

⁴For more information about IRMA (“I Reveal My Attributes”), see <https://www.irmacard.org>.

- an organisation O_{check} issues credentials giving the right to check the age of majority;
- a user C wants to watch a movie rated adult-only due to its violent contents; his has a credential from O_{age} with the attribute **adult**;
- a movie theatre V wants to verify whether the user has the right to watch this movie; it has a credential from O_{check} with the attribute **canCheckAdult**.

The scheme is informally given in Figure 12. n_V, n_C and n are fresh nonces. Functions $f_1/1, f_2/1$ and $f_3/2$ are independent hash functions; we thus model them as free constructor symbols. The construction $\text{SD}(\cdot; \cdot)$ is not modelled atomically and follows [25] but we do not describe here its details.

1. Verifier \rightarrow Client : $\text{dh}(g, n_V), \text{SD}(\text{canCheckAdult}; f_1(\text{dh}(g, n_V)))$
2. Client \rightarrow Verifier : $\text{dh}(g, n_C), \text{SD}(\emptyset; f_1(\text{dh}(g, n_V)), \text{dh}(g, n_C))$
3. Verifier \rightarrow Client : $\text{enc}(\langle 0x00, \text{ok} \rangle, k)$
4. Client \rightarrow Verifier : $\text{enc}(\langle 0x01, \text{ok} \rangle, k)$
5. Verifier \rightarrow Client : $\text{enc}(\langle n, \text{requestAdult} \rangle, k)$
6. Client \rightarrow Verifier : $\text{enc}(\langle \text{adult}, \text{SD}(\text{adult}; f_3(n, \text{seed})) \rangle, k)$

Fig. 12. ABCDH (where $\text{seed} = \text{dh}(\text{dh}(g, n_C), n_V)$ and $k = f_2(\text{seed})$)

This is a 2-party protocol that falls into our class. Actually, we have that $fn(\mathcal{I}) \neq \emptyset$ and $fn(\mathcal{R}) \neq \emptyset$, but $fn(\mathcal{I}) \cap fn(\mathcal{R}) = \emptyset$ (non-shared case). The complete model of this protocol is quite complex and can be found in [45]. Frame Opacity can be automatically established using the syntactic heuristic (see Section 5.3) in less than 40 seconds. The other heuristics were not enough precise to conclude (yielding negative results) showing the importance of having the choice between heuristics that are precise but less efficient and ones that are more efficient but less precise. Regarding well-authentication, due to the length of the protocol, the queries are also quite long. Because of the latter and the high complexity of the underlying term algebra, it required too much time for **ProVerif** to terminate. We addressed this performance issue by soundly splitting up big queries into smaller ones. This way, we successfully established well-authentication for this protocol within 3 hours.

6.6. DAA join & DAA sign

A Trusted Platform Module (TPM) is a hardware device aiming at protecting cryptographic keys and at performing some cryptographic operations. Typically, a user may authenticate himself to a service provider relying on such a TPM. The main advantage is to physically separate the very sensitive data from the rest of the system. On the downside however, such devices may be used by malicious agents to breach users' privacy by exploiting their TPMs. Direct Anonymous Attestation (DAA) protocols have been designed to let TPMs authenticate themselves whilst providing accountability and privacy.

In a nutshell, some issuers issue credentials representing membership to a group to the TPM using group signatures via the *DAA join* protocol. Those credentials are bound to the internal secret of the TPM that must remain unknown to the service provider. Then, when a TPM is willing to prove to a verifier its membership to a group, it uses the *DAA sign* protocol. We analysed the RSA-based DAA join and sign protocols as described in [44]. Both protocols rely on complex cryptographic primitives (*e.g.* blind signatures, commitments, and Zero Knowledge

proofs) but **ProVerif** can deal with them all. Note that the authors of [44] have automatically established a game-based version of unlinkability of the combination of DAA Join and DAA Sign using **ProVerif**. We only provide an analysis of each protocol in isolation since the combination of the two protocols is a 3-party protocol.

6.6.1. DAA join

In the RSA-based DAA join protocol, the TPM starts by sending a credential request in the form of a commitment containing its internal secret, some session nonce and the public key of the issuer. The issuer then challenges the TPM with some fresh nonces encrypted asymmetrically with the public key of the TPM. After having received the expected TPM's answer, the issuer sends a new nonce as second challenge. To this second challenge, the TPM needs to provide a ZK proof bound to this challenge proving that he knows the internal secret on which the previous commitment was bound. Finally, after verifying this proof, the issuer blindly signs the commitment allowing the TPM to extract the required credential.

1. TPM \rightarrow Issuer : N_I, U
2. Issuer \rightarrow TPM : $\text{penc}(n_e, n, \text{pk}(sk_{\text{TPM}}))$
3. TPM \rightarrow Issuer : $\text{h}((U, n_e))$
4. Issuer \rightarrow TPM : n_i
5. TPM \rightarrow Issuer : $n_t, \text{ZK}_{\text{join}}((tsk, n_v), (zeta_I, N_I, U, (n_t, n_i)))$
6. Issuer \rightarrow TPM : $\text{clsign}((U, r), sk_I)$

Fig. 13. DAA Join

We give in Figure 13 an Alice & Bob description of the protocol between the TPM and the issuer. The message $zeta_I = \text{h}((0, bsnI))$ relies on $bsnI$: using a fresh $bsnI$ allows to ensure that the session of DAA Join will be unlinkable from previous ones. The message $tsk = \text{h}((\text{h}((DAAseed, \text{h}(KI))), cnt, 0))$ combines the internal secret of the TPM (*i.e.* $DAAseed$) with the public long-term key of the issuer (*i.e.* KI). The commit message $N_I = \text{commit}(zeta_I, tsk)$ binds $zeta_I$ with the internal secret while the commit message $U = \text{clommit}(\text{pk}(sk_I), n_v, tsk)$ expresses a credential request for a signature key sk_I . The goal of the TPM will be to get the message U signed by the issuer. More precisely, the issuer will blindly sign the message U with the signature key sk_I after making sure that the TPM can decrypt challenges encrypted with its public key (step 2.) and that he can provide a fresh ZK proof showing he knows its internal secret binds in U and N_I (step 5.). Finally, if all checks are successful, the issuer will blindly sign the credential request U (step 6.). We note $\text{clsign}((U, r), sk_I)$ the blind signature of a commitment U with signature key sk_I and some random r . The function penc denotes a randomized asymmetric encryption scheme. Note that $\text{ZK}(\cdot, \cdot)$ has two arguments: the first one should contain private data and the second one should contain public data. One can always extract public data from ZK proofs and one can check if both public and private data match as expected.

This protocol falls in our class and lies in the shared case⁵ (*i.e.* $fn(\mathcal{I}) \cap fn(\mathcal{R}) = \{sk_{\text{TPM}}\}$). UKano automatically established frame opacity in less than 30 seconds using the syntactic idealisation,

⁵Both roles share the identity name sk_{TPM} (but note that the Issuer only uses $\text{pk}(sk_{\text{TPM}})$). Indeed, before executing the join protocol, the TPM and the issuer should establish a one-way authenticated channel that is not specified by the DAA scheme. Therefore, an Issuer session is associated to a single TPM's identity it is expected to communicate with.

and in less than 3 seconds when using the quasi-syntactic heuristic. Note that the semantic one is not precise enough to allow one to conclude. Regarding well-authentication, we had to leverage the same splitting technique explained in Section 6.5 so that UKano could conclude in a reasonable amount of time (around 30 seconds).

6.6.2. DAA sign

Once a TPM has obtained such a credential, it may prove its membership using the DAA sign protocol. This protocol is played by a TPM and a verifier: the verifier starts by challenging the TPM with a fresh nonce (step 1.), the latter then sends a complex ZK proof bound to this nonce (step 2.). The latter ZK proof also proves that the TPM knows a credential from the expected issuer bound to a secret he knows (essentially a message $\text{clsign}((U, r), sk_I)$ received in a previous session of DAA join). The verifier accepts only if the ZK can be successfully checked (step 3.).

We give in Figure 14 an Alice & Bob description of the protocol between a verifier and the TPM willing to sign a message m using its credential $cred = \text{clsign}((U, r), sk_I)$ he received from a past DAA join session. From its credential $cred$, the TPM will compute a new credential dedicated to the current sign session: $cred' = \text{clcommit}((pk(sk_I), cred), n_c)$. Indeed, if the TPM had directly used $cred$ then two sessions of DAA sign would have been trivially linkable. The TPM also computes a commit of tsk that was used to obtain the credential: $N_V = \text{commit}(tsk, zeta_V)$ where $zeta_V$ is a fresh nonce⁶.

1. Verifier \rightarrow TPM : n_v
2. TPM \rightarrow Verifier : $(zeta_V, pk(sk_I), N_V, cred', n_t, \text{ZK}_{\text{sign}}((tsk, n_c), (zeta_V, pk(sk_I), N_V, cred', (n_t, n_v, m))))$
3. Verifier \rightarrow TPM : accept/reject

Fig. 14. DAA Sign

This 2-party protocol falls in our class and lies in the non-shared case. Indeed, we model infinitely many different TPMs that may take part to the DAA sign protocol with any verifier whose role is always the same (he has no proper identity). We automatically analysed this protocol with UKano and established both frame opacity and well-authentication in less than 4 seconds. Frame opacity has been established using a well-chosen idealisation adapted from the syntactic heuristic.

6.6.3. Summary

We now summarise our results in Table 1. We notably indicate the verification time in seconds to verify both conditions. When there is an attack, we give the time ProVerif takes to show that one of the condition fails to hold. We note \checkmark for a condition automatically checked using our tool UKano and \times when the condition does not hold. Note that all positive results were established automatically using our tool UKano (which is based on ProVerif) without any manual effort (except for the cases indicated by \checkmark^* for which little manual efforts were needed).

⁶The protocol also specifies a mode that makes different signatures linkable by construction using $zeta_V = h((0, bsnV))$. We focus on the other mode for which unlinkability is expected to hold.

Protocol	Frame opacity	Well-auth.	Unlinkability	Verification time
Hash-Lock	✓	✓	safe	< 1s
Fixed LAK	✓	✓	safe	< 1s
BAC	✓	✓	safe	< 1s
BAC/PA/AA	✓	✓	safe	< 1s
BAC/AA/PA	✓	✓	safe	< 1s
PACE (faillible dec)	–	×	attack	< 30s
PACE (as in [17])	–	×	attack	< 1m
PACE	–	×	attack	< 2m
PACE with tags	✓	✓	safe	< 2m
DAA sign	✓	✓	safe	< 5s
DAA join	✓	✓*	safe	< 5s
ABCDH (irma)	✓	✓*	safe	< 3h

Table 1

Summary of our case studies (Section 6)

7. Conclusion

We have identified two conditions, namely well-authentication and frame opacity, which imply anonymity and unlinkability for a wide class of protocols. Additionally, we have shown that these two conditions can be checked automatically using the tool **ProVerif**, and we have mechanised their verification in our tool **UKano**. This yields a new verification technique to check anonymity and unlinkability for an unbounded number of sessions. It has proved quite effective on various case studies. In particular, it has brought first-time unlinkability proofs for the BAC protocol (e-passport) and ABCDH protocol. Our case studies also illustrated that our methodology is useful to discover attacks against unlinkability and anonymity as illustrated by the new attacks we found on PACE and LAK.

In the future, we plan to improve the way our sufficient conditions are checked. For instance, we would like to let **UKano** build idealisations in a cleverer way; notably in the choice of heuristics to adopt. We are also interested in other tools we may leverage as back-ends (*e.g.* **Tamarin**).

We also identify a number of research problems aimed at generalizing the impact of our technique. We would like to investigate the extension of our main theorem to the case of protocols with states. This is certainly technically challenging, but would make it possible to model more protocols, or at least model them more faithfully. We are also interested in extending our method to protocols with more than 2 parties which are commonplace (*e.g.* the combination of DAA join and DAA sign is essentially a 3-party protocol).

Further, we have identified a limitation of our well-authentication notion when analysing the PACE protocol (see Section 6.4). We would like to relax this condition in order to remain precise in such cases. We also believe that frame opacity could be verified via reachability and syntactical checks only. We think that seeking for such a result in a way that can be applied to real-world case studies is an attractive and exciting research goal since it would allow to completely reduce the verification of complex equivalence based-properties such as unlinkability into purely reachability verification problems that are known to be much simpler.

Finally, we believe that the overall methodology developed in this paper (*i.e.* privacy via sufficient conditions) could be applied in other contexts where privacy is critical: *e.g.* e-voting,

attribute-based credentials, blockchain technologies, transparent certificate authorities. In our opinion, the privacy via sufficient conditions approach also sheds light on the privacy notions themselves. Indeed, each sufficient condition helps to get a better grasp of necessary ingredients for preserving privacy. It thus might be interesting to translate such conditions into more comprehensive guidelines helping the design of new privacy-enhancing protocols.

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References

- [1] PKI for machine readable travel documents offering ICC read-only access. Technical report, International Civil Aviation Organization, 2004.
- [2] Iso 15408-2: Common criteria for information technology security evaluation - part 2: Security functional components, July 2009.
- [3] M. Abadi and B. Blanchet. Computer-assisted verification of a protocol for certified email. In *Static Analysis*, pages 316–335. Springer, 2003.
- [4] M. Abadi and C. Fournet. Mobile values, new names, and secure communication. In *Proceedings of POPL'01*. ACM Press, 2001.
- [5] G. Alpár and J.-H. Hoepman. A secure channel for attribute-based credentials:[short paper]. In *Proceedings of the 2013 ACM workshop on Digital identity management*, pages 13–18. ACM, 2013.
- [6] M. Arapinis, V. Cheval, and S. Delaune. Verifying privacy-type properties in a modular way. In *Proceedings of the 25th IEEE Computer Security Foundations Symposium (CSF'12)*, pages 95–109, Cambridge Massachusetts, USA, June 2012. IEEE Computer Society Press.
- [7] M. Arapinis, T. Chothia, E. Ritter, and M. Ryan. Analysing unlinkability and anonymity using the applied pi calculus. In *Proceedings of CSF'10*. IEEE Comp. Soc. Press, 2010.
- [8] M. Arapinis, L. Mancini, E. Ritter, M. Ryan, N. Golde, K. Redon, and R. Borgaonkar. New privacy issues in mobile telephony: fix and verification. In *Proceedings of the ACM conference on Computer and communications security*, pages 205–216. ACM, 2012.
- [9] M. Arapinis, L. I. Mancini, E. Ritter, and M. Ryan. Privacy through pseudonymity in mobile telephony systems. In *NDSS*, 2014.
- [10] Á. Armando, R. Carbone, L. Compagna, J. Cuéllar, and M. L. Tobarra. Formal analysis of SAML 2.0 web browser single sign-on: breaking the SAML-based single sign-on for Google apps. In *Proc. 6th ACM Workshop on Formal Methods in Security Engineering (FMSE'08)*, pages 1–10. ACM, 2008.
- [11] A. Armando et al. The AVANTSSAR platform for the automated validation of trust and security of service-oriented architectures. In *Proc. 18th International Conference on Tools and Algorithms for the Construction and Analysis of Systems (TACAS'12)*, volume 7214, pages 267–282. Springer, 2012.
- [12] M. Backes, C. Hritcu, and M. Maffei. Automated verification of remote electronic voting protocols in the applied pi-calculus. In *Proceedings of the 21st IEEE Computer Security Foundations Symposium, CSF 2008, Pittsburgh, Pennsylvania, 23-25 June 2008*, pages 195–209. IEEE Computer Society, 2008.
- [13] M. Backes, M. Maffei, and D. Unruh. Zero-knowledge in the applied pi-calculus and automated verification of the direct anonymous attestation protocol. In *Security and Privacy, 2008. SP 2008. IEEE Symposium on*, pages 202–215. IEEE, 2008.
- [14] D. Basin, J. Dreier, and R. Sasse. Automated symbolic proofs of observational equivalence. In *Proceedings of the 22nd ACM SIGSAC Conference on Computer and Communications Security*, pages 1144–1155. ACM, 2015.
- [15] M. Baudet. Deciding security of protocols against off-line guessing attacks. In *Proc. 12th Conference on Computer and Communications Security*. ACM, 2005.
- [16] J. Bender, Ö. Dagdelen, M. Fischlin, and D. Kügler. The pace aa protocol for machine readable travel documents, and its security. In *Financial Cryptography and Data Security*, pages 344–358. Springer, 2012.
- [17] J. Bender, M. Fischlin, and D. Kügler. Security analysis of the pace key-agreement protocol. In *Information Security*, pages 33–48. Springer, 2009.
- [18] B. Blanchet. An Efficient Cryptographic Protocol Verifier Based on Prolog Rules. In *Proceedings of CSF'01*, pages 82–96. IEEE Comp. Soc. Press, 2001.

- [19] B. Blanchet, M. Abadi, and C. Fournet. Automated verification of selected equivalences for security protocols. *Journal of Logic and Algebraic Programming*, 2008.
- [20] B. Blanchet and B. Smyth. Automated reasoning for equivalences in the applied pi calculus with barriers. In *Proc. 29th Computer Security Foundations Symposium*, 2016.
- [21] M. Brusó. *Dissecting Unlinkability*. PhD thesis, Technische Universiteit Eindhoven, 2014.
- [22] M. Brusó, K. Chatzikokolakis, and J. den Hartog. Formal verification of privacy for RFID systems. In *Proceedings of CSF'10*, 2010.
- [23] M. Brusó, K. Chatzikokolakis, S. Etalle, and J. Den Hartog. Linking unlinkability. In *Trustworthy Global Computing*, pages 129–144. Springer, 2012.
- [24] J. Camenisch, A. Lehmann, and G. Neven. Electronic identities need private credentials. *IEEE Security & Privacy*, 10(1):80–83, 2012.
- [25] J. Camenisch, S. Mödersheim, and D. Sommer. A formal model of identity mixer. In *Formal Methods for Industrial Critical Systems*, pages 198–214. Springer, 2010.
- [26] L. Cheikhrouhou, W. Stephan, Ö. Dagdelen, M. Fischlin, and M. Ullmann. Merging the cryptographic security analysis and the algebraic-logic security proof of pace. In *Sicherheit*, pages 83–94, 2012.
- [27] V. Cheval and B. Blanchet. Proving more observational equivalences with ProVerif. In *Proc. 2nd Conference on Principles of Security and Trust*, volume 7796 of *LNCS*, pages 226–246. Springer, 2013.
- [28] V. Cheval, H. Comon-Lundh, and S. Delaune. Trace equivalence decision: Negative tests and non-determinism. In *Proceedings of CCS'11*. ACM Press, 2011.
- [29] R. Chrétien, V. Cortier, and S. Delaune. From security protocols to pushdown automata. *ACM Transactions on Computational Logic*, 17(1:3), Sept. 2015.
- [30] V. Cortier, S. Delaune, and P. Lafourcade. A survey of algebraic properties used in cryptographic protocols. *Journal of Computer Security*, 14(1):1–43, 2006.
- [31] V. Cortier and B. Smyth. Attacking and fixing Helios: An analysis of ballot secrecy. *Journal of Computer Security*, 21(1):89–148, 2013.
- [32] S. Delaune and L. Hirschi. A survey of symbolic methods for establishing equivalence-based properties in cryptographic protocols. *Journal of Logical and Algebraic Methods in Programming*, 2016.
- [33] S. Delaune, S. Kremer, and M. D. Ryan. Verifying privacy-type properties of electronic voting protocols. *Journal of Computer Security*, (4), 2008.
- [34] S. Delaune, M. D. Ryan, and B. Smyth. Automatic verification of privacy properties in the applied pi-calculus. In *Proceedings of the 2nd Joint iTrust and PST Conferences on Privacy, Trust Management and Security (IFIPTM'08)*, volume 263 of *IFIP Conference Proceedings*. Springer, 2008.
- [35] N. Dong, H. Jonker, and J. Pang. Formal analysis of privacy in an ehealth protocol. In *Computer Security—ESORICS 2012*, pages 325–342. Springer, 2012.
- [36] M. Feldhofer, S. Dominikus, and J. Wolkerstorfer. Strong authentication for RFID systems using the AES algorithm. In *Cryptographic Hardware and Embedded Systems—CHES 2004*, pages 357–370. Springer, 2004.
- [37] L. Hirschi. *Automated Verification of Privacy in Security Protocols: Back and Forth Between Theory & Practice*. PhD thesis, École Normale Supérieure Paris-Saclay, April 2017.
- [38] L. Hirschi, D. Baelde, and S. Delaune. A method for verifying privacy-type properties: the unbounded case. In *Proceedings of the 37th IEEE Symposium on Security and Privacy (S&P'16)*, San Jose, California, USA, May 2016. IEEE Computer Society Press.
- [39] A. Juels and S. A. Weis. Defining strong privacy for RFID. *ACM Transactions on Information and System Security (TISSEC)*, 13(1):7, 2009.
- [40] S. Lee, T. Asano, and K. Kim. RFID mutual authentication scheme based on synchronized secret information. In *Symposium on cryptography and information security*, 2006.
- [41] S. Meier, B. Schmidt, C. Cremers, and D. Basin. The Tamarin Prover for the Symbolic Analysis of Security Protocols. In *Proc. 25th International Conference on Computer Aided Verification (CAV'13)*, volume 8044 of *LNCS*, pages 696–701. Springer, 2013.
- [42] C. Paquin and G. Zaverucha. U-prove cryptographic specification v1.1 (revision 3), December 2013.
- [43] S. Santiago, S. Escobar, C. Meadows, and J. Meseguer. A formal definition of protocol indistinguishability and its verification using maude-mpa. In *Security and Trust Management*, pages 162–177. Springer, 2014.
- [44] B. Smyth, M. D. Ryan, and L. Chen. Formal analysis of privacy in direct anonymous attestation schemes. *Science of Computer Programming*, 111:300–317, 2015.
- [45] UKano tool and case studies. <http://projects.lsv.ens-cachan.fr/ukano/>. Accessed: 30-09-2017.
- [46] T. Van Deursen and S. Radomirovic. Attacks on RFID protocols. *IACR Cryptology ePrint Archive*, 2008:310, 2008.

Appendix

We provide in this appendix the proof of our main result (Theorem 1). Our main argument consists in showing that, for any execution of $\mathcal{M}_{\Pi, \overline{id}}$, there is an indistinguishable execution of \mathcal{S}_{Π} (the other direction being easy). This indistinguishable execution will be obtained by a modification of the involved agents. We will proceed via a renaming of agents applied to an abstraction of the given execution of $\mathcal{M}_{\Pi, \overline{id}}$. We then prove that the renamed executions can still be executed and produce an indistinguishable frame.

We fix a protocol $\Pi = (\overline{k}, \overline{n}_I, \overline{n}_R, \dagger_I, \dagger_R, \mathcal{I}, \mathcal{R})$, some identity names \overline{id} and some fresh constants \overline{id}_0 yielding a process $\mathcal{M}_{\Pi, \overline{id}}$ as defined in Section 3. We denote \overline{id}_i (resp id_i , k_i , and k'_i) the i^{th} element of the sequence \overline{id}_0 (resp. \overline{id} , \overline{k} , and \overline{k}'). The construction of the proof will slightly differ depending on \dagger_I, \dagger_R (sequential vs concurrent sessions) and whether $fn(\mathcal{I}) \cap fn(\mathcal{R}) = \emptyset$ or not (non-shared case vs shared case).

A. Abstraction of configurations

Instead of working with $\mathcal{M}_{\Pi, \overline{id}}$, \mathcal{M}_{Π} , and \mathcal{S}_{Π} , it will be more convenient to work with *ground configurations*. Intuitively, we will associate to each execution of $\mathcal{M}_{\Pi, \overline{id}}$, \mathcal{M}_{Π} , and \mathcal{S}_{Π} , a ground configuration that contains all agents involved in that execution, already correctly instantiated. By doing so, we are able to get rid of technical details such as unfolding replications and repetitions a necessary number of times, create necessary identity and session parameters, etc. These ground configurations are generated from sequences of annotations satisfying some requirements.

A.1. Sequences of annotations

The sequence of annotations from which we will build ground configurations shall satisfy some requirements that we list below. Essentially, the goal is to make sure that no freshness condition over session and identity names is violated.

Definition 20. *A sequence S of annotations is well-formed if the following conditions hold.*

- In all annotations $A(\overline{k}', \overline{n}')$ with $A \in \{I, R\}$, the session parameters \overline{n}' are names, and the identity parameters \overline{k}' are made of names or constants \overline{id}_0 . We also have that $|\overline{n}'| = |\overline{n}_A|$ and $|\overline{k}'| = |\overline{k}|$. Moreover, when $\overline{id}_0 \cap \overline{k}' \neq \emptyset$, $k'_i = \overline{id}_{0_j}$ if, and only if, $k_i = id_j$.
- No name appears both as identity and session parameter in any two annotations.
- Two different annotations never share a session parameter.
- Two annotations either have the same identity parameters, or do not share any identity parameter at all.

We say that a sequence of annotations S is *single-session* when two different annotations of the same role never share an identity parameter and no annotation contains a constant in \overline{id}_0 .

We straightforwardly lift those definitions to annotated traces by only keeping the underlying sequence of annotations and dropping actions. A well-formed (resp. well-formed, single-session) sequence of annotations contains annotations of agents that can be instantiated from $\mathcal{M}_{\Pi, \overline{id}}$ (resp. \mathcal{S}_{Π}). Conversely, we may note that given an annotated trace \mathbf{ta} such that $\mathcal{M}_{\Pi, \overline{id}} \xrightarrow{\mathbf{ta}} K'$, we have that \mathbf{ta} is well-formed.

A.2. Ground configurations

After the introduction of some notations, we explain how *ground configurations* are obtained from well-formed sequences of annotations. Given a well-formed sequence of annotations S , and some role $A \in \{I, R\}$, we introduce the following notations:

- $\text{id}_A(S)$ is the set of identity parameters of agents of role A occurring in S , i.e.

$$\text{id}_A(S) = \{\bar{k} \mid A(\bar{k}, \bar{n}) \in S\}.$$

- for $\bar{l} \in \text{id}_A(S)$, we note $\text{sess}_A(S, \bar{l})$ the set of session parameters of agents of role A and identity parameters \bar{l} occurring in S , i.e. $\text{sess}_A(S, \bar{l}) = \{\bar{n} \mid A(\bar{l}, \bar{n}) \in S\}$.
- for $\bar{l} \in \text{id}_A(S)$, we note $\text{sess}_A^{\text{seq}}(S, \bar{l})$ the sequence made of elements from $\text{sess}_A(S, \bar{l})$, without repetition, in order of first occurrence in S , i.e.

Finally, for some sequence of elements $L = e_1, e_2, e_3, \dots$ and a process $P(e)$ parametrized by e , we denote by $\prod_{e \in L} P(e)$ the process $P(e_1); (P(e_2)); (P(e_3)); \dots$.

Definition 21. Let S be a well-formed sequence of annotations. The ground configuration associated to S , denoted by $\mathcal{K}(S)$, is the multiset $\mathcal{P}_I \sqcup \mathcal{P}_R$ where \mathcal{P}_I is defined as follows depending on \dagger_I :

- if $\dagger_I = !$ then $\mathcal{P}_I = \left\{ (\mathcal{I}\{\bar{k} \mapsto \bar{l}, \bar{n}_I \mapsto \bar{m}\})[I(\bar{l}, \bar{m})] \mid I(\bar{l}, \bar{m}) \in S \right\}$;
- if $\dagger_I = i$ then $\mathcal{P}_I = \left\{ \prod_{\bar{m} \in S_I} (\mathcal{I}\{\bar{k} \mapsto \bar{l}, \bar{n}_I \mapsto \bar{m}\})[I(\bar{l}, \bar{m})] \mid \bar{l} \in \text{id}_I(S) \text{ and } S_I = \text{sess}_I^{\text{seq}}(S, \bar{l}) \right\}$.

The multiset \mathcal{P}_R is computed in a similar way, replacing \mathcal{I} , \bar{n}_I and I by \mathcal{R} , \bar{n}_R and R respectively.

Example 30. Consider the following toy protocol $\Pi_{\text{toy}} := (k, n_I, n_R, i, \mathcal{I}, \mathcal{R})$ where $\mathcal{I} = \text{out}(c_I, \text{enc}(n_I, k))$ and $\mathcal{R} = \text{in}(c_R, x)$. We have that

$$\mathcal{M}_{\Pi_{\text{toy}}} = ! \text{ new } k. (i \text{ new } n_I. \mathcal{I} \mid i \text{ new } n_R. \mathcal{R}) \xrightarrow{\text{ta}} (\mathcal{Q}; \phi)$$

for $\text{ta} = \tau. \tau. \tau. \tau. \tau. \ell : \text{out}(c_I, w_0)[I(k, n_I)]. \tau. \tau. \tau. \ell : \text{out}(c_I, w_1)[I(k, n'_I)]$. The ground configuration associated to ta is the following multiset with one element:

$$\mathcal{K}(\text{ta}) = \{(\text{out}(c_I, \text{enc}(n_I, k))[I(k, n_I)]); (\text{out}(c_I, \text{enc}(n'_I, k))[I(k, n'_I)])\}.$$

Note that $\mathcal{K}(\text{ta})$ is also able to produce the annotated trace ta up to some τ actions.

We lift those definitions to annotated traces as before. A ground configuration associated to a well-formed sequence of annotations is essentially an “unfolding” of $\mathcal{M}_{\Pi, \bar{id}}$. Therefore, there is a strong relationship between the original process and the one obtained through $\mathcal{K}(\cdot)$ as established in the following proposition.

Proposition 3. Let ta be a well-formed annotated trace. We have that:

- (1) If $\mathcal{M}_{\Pi, \bar{id}} \xrightarrow{\text{ta}} K$ (resp. $\mathcal{S}_{\Pi} \xrightarrow{\text{ta}} K$), then $\mathcal{K}(\text{ta}) \xrightarrow{\text{ta}} K'$ for some K' such that $\phi(K) = \phi(K')$.
- (2) If $\mathcal{K}(\text{ta}) \xrightarrow{\text{ta}} K$, then $\mathcal{M}_{\Pi, \bar{id}} \xrightarrow{\text{ta}} K'$ for some K' such that $\phi(K) = \phi(K')$.

- (3) If $\mathcal{K}(\mathbf{ta}) \xrightarrow{\mathbf{ta}} K$ and \mathbf{ta} is single-session, then $\mathcal{S}_{\Pi} \xrightarrow{\mathbf{ta}} K'$ for some K' such that $\phi(K) = \phi(K')$.
- (4) If $\mathbf{ta} = \mathbf{ta}_1.\mathbf{ta}_2$ and $\mathcal{K}(\mathbf{ta}_1.\mathbf{ta}_2) \xrightarrow{\mathbf{ta}_1} K$ then $\mathcal{K}(\mathbf{ta}_1) \xrightarrow{\mathbf{ta}_1} K'$ for some K' such that $\phi(K) = \phi(K')$.

Proof. Item (1) holds by construction of the operator $\mathcal{K}(\cdot)$, which has been built by closely mimicking how $\mathcal{M}_{\Pi, \bar{id}}$ and \mathcal{S}_{Π} create agents. We thus have that when an agent is at top-level in a configuration in the execution of $\mathcal{M}_{\Pi, \bar{id}}$ (or \mathcal{S}_{Π}) then it is also available in the execution of $\mathcal{K}(\mathbf{ta})$. In general, less τ actions are necessary for the execution starting with $\mathcal{K}(\mathbf{ta})$ than for the executions starting with $\mathcal{M}_{\Pi, \bar{id}}$ or \mathcal{S}_{Π} . Indeed, there is no need, in ground configurations, to spawn agents by unfolding replications or repetitions or creating fresh names. This is because agents are (more) immediately available in $\mathcal{K}(\mathbf{ta})$.

Item (2) heavily relies on the well-formedness of \mathbf{ta} . One can thus prove that all agents in $\mathcal{K}(\mathbf{ta})$ can be created along the execution by choosing appropriate names when triggering rules NEW. For instance, the first item of Definition 20 makes sure that the arity of parameters in agents matches the number of names to be created. The second and third items of Definition 20 ensure that the freshness guard conditions of the rule NEW holds for names to be created. Finally, the fourth item of Definition 20 implies that when an agent $a = A(\bar{k}, \bar{n})$ must be created then either (i) names in \bar{k} are completely fresh and this identity \bar{k} can be created from $\mathcal{M}_{\Pi, \bar{id}}$ by unfolding ! and create names \bar{k} or (ii) names in \bar{k} have already been created and thus the agent a can be created from the last replicated process used to create identity \bar{k} in the first place.

Item (3) is similar to (2). The single-session hypothesis provides exactly what is needed to mimic the execution using \mathcal{S}_{Π} rather than $\mathcal{M}_{\Pi, \bar{id}}$.

Finally, item (4) stems from a simple observation. Compared to $\mathcal{K}(\mathbf{ta}_1)$, the multiset of processes $\mathcal{K}(\mathbf{ta}_1.\mathbf{ta}_2)$ adds processes in parallel and in sequence after some processes of $\mathcal{K}(\mathbf{ta}_1)$. However, these extra processes are unused when executing \mathbf{ta}_1 , thus $\mathcal{K}(\mathbf{ta}_1)$ can perform the same execution. \square

A.3. Renamings of annotations

As mentioned before, we shall prove that for any execution of $\mathcal{M}_{\Pi, \bar{id}}$, there is an indistinguishable execution of \mathcal{S}_{Π} . This indistinguishable execution that \mathcal{S}_{Π} can perform will be obtained by a renaming of annotations. We define next a generic notion of such renamings of annotations. However, the crux of the final proof is to find a *good* renaming that implies: (i) the executability by \mathcal{S}_{Π} of the renamed trace, and (ii) the static indistinguishability of the resulting frames (before and after the renaming).

Definition 22. A renaming of annotations (denoted by ρ) is an injective mapping from annotations to annotations such that:

- for any well-formed sequence of annotations S , $S\rho$ is well-formed;
- ρ is role-preserving: i.e. initiator (resp. responder) annotations are mapped to initiator (resp. responder) annotations;
- for any two annotations $a_1 = A_1(\bar{k}_1, \bar{n}_1)$, $a_2 = A_2(\bar{k}_2, \bar{n}_2)$, if $\rho(a_1)$ and $\rho(a_2)$ have the same identity parameters, then $\bar{k}_1 = \bar{k}_2$.

The two first conditions are expected: renaming of annotations shall only modify session and identity parameters whilst preserving well-formedness. The final condition ensures that renamings do not create more “sequential dependencies” between agents (*i.e.* agents sharing the same identity and whose role can execute sessions only sequentially): after renaming, less pairs of agents have same identity.

Next, we define $\mathbf{ta}\rho$ as the annotated trace obtained from \mathbf{ta} by applying ρ to annotations only. Note that, by definition of renamings, the resulting $\mathbf{ta}\rho$ is well-formed as well.

One can also define the effect of renamings on ground configurations. If $\rho(A(\bar{k}, \bar{n})) = A(\bar{k}', \bar{n}')$, the renaming σ induced by ρ on $A(\bar{k}, \bar{n})$ is the (injective) mapping such that $\bar{k}\sigma = \bar{k}'$ and $\bar{n}\sigma = \bar{n}'$. Given a ground configuration $\mathcal{P} = \{\coprod_j P_j^i[a_j^i]\}_i$, we define $\mathcal{P}\rho = \{\coprod_j P_j^i\sigma_j^i[\rho(a_j^i)]\}_i$ where σ_j^i is the renaming induced by ρ on a_j^i . Note that the renaming on parameters induced by a renaming of annotations may conflict: this happens, for example, when $\rho(A(\bar{k}, \bar{n})) = A(\bar{k}_1, \bar{n})$ and $\rho(A(\bar{k}, \bar{m})) = A(\bar{k}_2, \bar{m})$.

A renaming of annotations can break executability. Even when executability is preserved, it is not obvious to relate processes before and after the renaming, as messages can be affected in complex ways and conditionals may not evaluate to the same outcome. Fortunately, frame opacity and well-authentication will provide us with strong properties to reason over executions, as seen in the next subsections.

Example 31. Consider the annotated trace \mathbf{ta} from Example 17 that $\mathcal{M}_{\Pi, \bar{id}}$ can execute. The ground configuration $\mathcal{K}(\mathbf{ta})$ can execute it as well, using \Rightarrow . We now define ρ as follows: $\rho(I(k', n'_I)) = I(k_1, n'_I)$ and $\rho(R(k', n'_R)) = R(k_2, n'_R)$ for some fresh names k_1, k_2 . The trace $\mathbf{ta}\rho$ can no longer be executed by $\mathcal{M}_{\Pi, \bar{id}}$ nor by $\mathcal{K}(\mathbf{ta})\rho$ (even using \Rightarrow) because the first output sent by $R(k_2, n'_R)$ (*i.e.* $\text{enc}(\langle n'_I, n'_R \rangle, k_2)$) will not be accepted by $I(k_1, n'_I)$ since $k_1 \neq k_2$.

B. Control is determined by associations

We show in that section that the outcome of tests is entirely determined by associations. This will be useful to show that, if we modify an execution (by renaming agents) while preserving enough associations, then the control flow is left unchanged.

Proposition 4. We assume that Π satisfies item (i) of the well-authentication condition. Let $\mathbf{ta} = \mathbf{ta}_0.\tau_x[a_1]$ with $\tau_x \in \{\tau_{\text{then}}, \tau_{\text{else}}\}$ be a well-formed annotated trace such that

$$\mathcal{K}(\mathbf{ta}) \xrightarrow{\mathbf{ta}_0.\tau_x[a_1]} (\mathcal{P}; \phi)$$

and the last action (*i.e.* $\tau_x[a_1]$) is performed by an unsafe conditional. We have that $\tau_x = \tau_{\text{then}}$ if, and only if, there exists $a_2 \in \mathcal{A}$ such that a_1 and a_2 are associated in (\mathbf{ta}_0, ϕ) .

Proof. (\Rightarrow) We start by applying Proposition 3 to obtain an execution

$$\mathcal{M}_{\Pi, \bar{id}} \xrightarrow{\mathbf{ta}_0.\tau_{\text{then}}[a_1]} (\mathcal{P}'; \phi) \text{ and thus } \mathcal{M}_{\Pi, \bar{id}} \xrightarrow{\mathbf{ta}_0^*.\tau_{\text{then}}[a_1]} (\mathcal{P}''; \phi).$$

for some $\mathbf{ta}_0^* \stackrel{\tau}{=} \mathbf{ta}_0$. As a consequence of well-authentication, item (i) applied on the above execution, we obtain that for some $a_2 \in \mathcal{A}$, a_1 and a_2 are associated in (\mathbf{ta}_0^*, ϕ) . Since $\mathbf{ta}_0 \stackrel{\tau}{=} \mathbf{ta}_0^*$, they are also associated in (\mathbf{ta}_0, ϕ) .

(\Leftarrow) For this other direction, we observe that (up to changes of recipes that do not affect the resulting messages) if two agents are associated in the above execution (starting with $\mathcal{K}(\mathbf{ta})$), then they are executing *the* honest trace of Π modulo a renaming of parameters, thus the considered test must be successful. We thus assume that $a_1 = A(\bar{k}_1, \bar{n}_1)$ and $a_2 = A(\bar{k}_2, \bar{n}_2)$ are associated in (\mathbf{ta}_0, ϕ) we shall prove that $\tau_x = \tau_{\text{then}}$. By association, $\mathbf{ta}_0|_{a_1, a_2}$ is honest: its observable actions are of the form $\text{out}(c_1, w_1). \text{in}(c'_1, M_1) \dots \text{out}(c_n, w_n). \text{in}(c'_n, M_n)$ with possibly an extra output at the end, and are such that $M_i \phi \Downarrow_{=E} w_i \phi$ for all $1 \leq i \leq n$. Consider \mathbf{ta}' obtained from \mathbf{ta}_0 by replacing each recipe M_i by w_i . Since this change of recipes does not affect the resulting messages, the modified trace can still be executed by $\mathcal{K}(\mathbf{ta})$ and yields the same configuration $(\mathcal{P}; \phi)$. But now $\mathbf{ta}'|_{a_1, a_2}$ is a self-contained execution, *i.e.* if P and Q are the processes (possibly sub-processes) respectively annotated a_1 and a_2 in $\mathcal{K}(\mathbf{ta})$, we have:

$$(\{P[a_1], Q[a_2]\}; \emptyset) \xrightarrow{\mathbf{ta}'|_{a_1, a_2}} (\{P'[a_1], Q'[a_2]\}; \phi') \xrightarrow{\tau_x[a_1]} (\{P''[a_1], Q'[a_2]\}; \phi').$$

In the shared case (*i.e.* $fn(\mathcal{I}) \cap fn(\mathcal{R}) \neq \emptyset$), by definition of association, the identity parameters of a_1 are equal to those of a_2 . Otherwise, it holds that $fn(\mathcal{I}) \cap fn(\mathcal{R}) = \emptyset$. In both cases, we thus have:

$$\begin{aligned} (\{\text{new } \bar{k}.(\text{new } \bar{n}_I.\mathcal{I} \mid \text{new } \bar{n}_R.\mathcal{R})\}; \emptyset) &\xrightarrow{\tau^*} (\{P[a_1], Q[a_2]\}; \emptyset) \\ &\xrightarrow{\mathbf{ta}'|_{a_1, a_2}} (\{P'[a_1], Q'[a_2]\}; \phi') \\ &\xrightarrow{\tau_x[a_1]} (\{P''[a_1], Q'[a_2]\}; \phi'). \end{aligned}$$

In that execution, everything is deterministic (up to the equational theory) and thus the execution is actually a prefix of *the* honest execution of Π (from the process P_Π defined in Definition 5), up to a bijective renaming of parameters (note that P and Q do not share session parameters). Remind that all tests must be positive in the honest execution (*i.e.* τ_{else} does not occur in the honest execution). Therefore, $\tau_x = \tau_{\text{then}}$ concluding the proof. \square

C. Invariance of frame idealisations

In general, a renaming of annotations can break executability: as illustrated in Example 31, mapping two dual annotations to annotations with different identities breaks the ability of the two underlying agents to communicate successfully. Moreover, even when executability is preserved, parameters change (so do names) and thus frames are modified. However, as stated next in Proposition 5, such renamings do not change idealised frames. We obtain the latter since we made sure that idealised frames only depend on what is already observable and not on specific identity or session parameters. In combination with frame opacity, this will imply (Proposition 6) that a renaming of annotations has no observable effect on the resulting *real* frames.

Proposition 5. *Let \mathbf{ta} be an annotated trace such that $\Phi_{\text{ideal}}(\mathbf{ta})$ is well-defined. Let ρ be a renaming of annotations. We have that $\Phi_{\text{ideal}}(\mathbf{ta}) \sim \Phi_{\text{ideal}}(\mathbf{ta}\rho)$.*

Proof. Let \mathbf{ta} be an annotated trace such that $\Phi_{\text{ideal}}(\mathbf{ta})$ is well-defined. Let ρ be a renaming of annotations. Let fr_1 be an arbitrary name assignment, and fr_2 be an injective function satisfying $\text{fr}_2(a\rho, x) = \text{fr}_1(a, x)$. First, we show, by induction on \mathbf{ta} , that $\Phi_{\text{ideal}}^{\text{fr}_1}(\mathbf{ta}) = \Phi_{\text{ideal}}^{\text{fr}_2}(\mathbf{ta}\rho)$. The only interesting case is when $\mathbf{ta} = \mathbf{ta}_0.(\ell : \text{out}(c, w)[a])$. In such a case, we have that:

$$\Phi_{\text{ideal}}^{\text{fr}_1}(\mathbf{ta}_0.(\ell : \text{out}(c, w)[a])) = \Phi_{\text{ideal}}^{\text{fr}_1}(\mathbf{ta}_0) \cup \{w \mapsto \text{ideal}(\ell)\sigma_1^i\sigma_1^n\downarrow\}$$

with $\sigma_1^n(x_j^n) = \text{fr}_1(a, x_j^n)$ and $\sigma_1^i(x_j^i) = R_j\Phi_{\text{ideal}}^{\text{fr}_1}(\mathbf{ta}_0)$ where R_j is the j -th input of a in \mathbf{ta}_0 . The idealised frame $\Phi_{\text{ideal}}^{\text{fr}_2}(\mathbf{ta}\rho)$ is defined similarly, *i.e.*

$$\Phi_{\text{ideal}}^{\text{fr}_2}(\mathbf{ta}_0\rho.(\ell : \text{out}(c, w)[a\rho])) = \Phi_{\text{ideal}}^{\text{fr}_2}(\mathbf{ta}_0\rho) \cup \{w \mapsto \text{ideal}(\ell)\sigma_2^i\sigma_2^n\downarrow\}$$

with $\sigma_2^n(x_j^n) = \text{fr}_2(a\rho, x_j^n)$ and $\sigma_2^i(x_j^i) = R_j^{\rho}\Phi_{\text{ideal}}^{\text{fr}_2}(\mathbf{ta}_0\rho)$ where R_j^{ρ} is the j -th input of $a\rho$ in $\mathbf{ta}_0\rho$. By induction hypothesis we know that $\Phi_{\text{ideal}}^{\text{fr}_1}(\mathbf{ta}_0) = \Phi_{\text{ideal}}^{\text{fr}_2}(\mathbf{ta}_0\rho)$. Therefore, to conclude, it remains to show that $\text{ideal}(\ell)\sigma_1^i\sigma_1^n = \text{ideal}(\ell)\sigma_2^i\sigma_2^n$. Actually, we have that $R_j^{\rho} = R_j$, thus $\sigma_1^i(x_j^i) = \sigma_2^i(x_j^i)$, and $\sigma_2^n(x_j^n) = \text{fr}_2(a\rho, x_j^n) = \text{fr}_1(a, x_j^n) = \sigma_1^n(x_j^n)$.

We have shown that $\Phi_{\text{ideal}}^{\text{fr}_1}(\mathbf{ta}) = \Phi_{\text{ideal}}^{\text{fr}_2}(\mathbf{ta}\rho)$ and relying on Proposition 1, we easily deduce that $\Phi_{\text{ideal}}(\mathbf{ta}) \sim \Phi_{\text{ideal}}(\mathbf{ta}\rho)$. \square

Proposition 6. *We assume that Π satisfies frame opacity. Let ρ be a renaming of annotations and \mathbf{ta} be a well-formed annotated trace. If $\mathcal{K}(\mathbf{ta}) \xrightarrow{\mathbf{ta}} (\mathcal{P}_1; \phi_1)$ and $\mathcal{K}(\mathbf{ta}\rho) \xrightarrow{\mathbf{ta}\rho} (\mathcal{P}_2; \phi_2)$, then we have that $\phi_1 \sim \phi_2$.*

Proof. We start by applying Proposition 3 on the two given executions to obtain two executions starting from $\mathcal{M}_{\Pi, \bar{id}}$:

- $\mathcal{M}_{\Pi, \bar{id}} \xrightarrow{\mathbf{ta}^*} (\mathcal{P}'_1; \phi_1)$ with $\mathbf{ta}^* \stackrel{\tau}{=} \mathbf{ta}$; and
- $\mathcal{M}_{\Pi, \bar{id}} \xrightarrow{\mathbf{ta}^*_\rho} (\mathcal{P}'_2; \phi_2)$ with $\mathbf{ta}^*_\rho \stackrel{\tau}{=} \mathbf{ta}\rho$.

Relying on frame opacity, we know that $\Phi_{\text{ideal}}(\mathbf{ta}^*)$ (resp. $\Phi_{\text{ideal}}(\mathbf{ta}^*_\rho)$) is well-defined and $\Phi_{\text{ideal}}(\mathbf{ta}^*) \sim \phi_1$ (resp. $\Phi_{\text{ideal}}(\mathbf{ta}^*_\rho) \sim \phi_2$).

Note that, if \mathbf{ta}_1 and \mathbf{ta}_2 are two annotated traces such that $\mathbf{ta}_1 \stackrel{\tau}{=} \mathbf{ta}_2$ and fr_1 is a name assignment, then $\Phi_{\text{ideal}}^{\text{fr}_1}(\mathbf{ta}_1) = \Phi_{\text{ideal}}^{\text{fr}_1}(\mathbf{ta}_2)$. Thanks to this remark, we easily deduce that $\Phi_{\text{ideal}}(\mathbf{ta}) \sim \Phi_{\text{ideal}}(\mathbf{ta}^*)$ and $\Phi_{\text{ideal}}(\mathbf{ta}\rho) = \Phi_{\text{ideal}}(\mathbf{ta}^*_\rho)$. Thanks to Proposition 5, we know that $\Phi_{\text{ideal}}(\mathbf{ta}) \sim \Phi_{\text{ideal}}(\mathbf{ta}\rho)$ and by transitivity of \sim , we conclude that $\phi_1 \sim \phi_2$. \square

D. A sufficient condition for preserving executability

We can now state a key lemma (Lemma 2), identifying a class of renamings which yield indistinguishable executions. More precisely, this lemma shows that for renamings satisfying some requirements, if $\mathcal{K}(\mathbf{ta})$ can execute an annotated trace \mathbf{ta} then $\mathcal{K}(\mathbf{ta})\rho$ has an indistinguishable execution following the annotated trace $\mathbf{ta}\rho$. Remark that, in the conclusion, the renaming is applied after building the ground configuration $(\mathcal{K}(\mathbf{ta})\rho)$ instead of building the ground configuration

of the renamed trace $(\mathcal{K}(\mathbf{ta}\rho))$. Both variants are a priori different. However, in the final proof and in order to leverage previous propositions, we will need to relate executions of $\mathcal{K}(\mathbf{ta})$ with executions of $\mathcal{K}(\mathbf{ta}\rho)$. The following easy proposition bridges this gap. We also state and prove a variant of Proposition 3, item (4) when ρ is applied after building the ground configuration.

Proposition 7. *Let \mathbf{ta} be a well-formed annotated trace and ρ be a renaming of annotations.*

If $\mathcal{K}(\mathbf{ta})\rho \xrightarrow{\mathbf{ta}\rho} (\mathcal{P}'; \phi)$ then $\mathcal{K}(\mathbf{ta}\rho) \xRightarrow{\mathbf{ta}\rho} (\mathcal{P}''; \phi)$.

Proof. Essentially, the proposition follows from the fact that there are less agents in sequence in $\mathcal{K}(\mathbf{ta}\rho)$ than in $\mathcal{K}(\mathbf{ta})\rho$, thanks to the third item of Definition 22.

More formally, by considering $\mathcal{K}(\mathbf{ta}\rho)$ and $\mathcal{K}(\mathbf{ta})\rho$ as multiset of processes without sequence (by removing all sequences and taking the union of processes), we obtain the same multisets. Next, it suffices to prove that no execution is blocked by a sequence in $\mathcal{K}(\mathbf{ta}\rho)$. By definition of the renaming ρ (third requirement in Definition 22), if an agent $P[\rho(a)]$ occurring in $\mathcal{K}(\mathbf{ta}\rho)$ is in sequence with an agent $\rho(a')$ before him, then $P[a\rho]$ occurring in $(\mathcal{K}(\mathbf{ta})\rho)$ must be in sequence with a before him as well. Hence, when a process $P[\rho(a)]; Q$ is available (*i.e.* at top-level) at some point in the execution from $\mathcal{K}(\mathbf{ta})\rho$, then a similar process $P[\rho(a)]; Q'$ is also available at the same point in the execution from $\mathcal{K}(\mathbf{ta}\rho)$. However, a process may become available in the execution from $\mathcal{K}(\mathbf{ta})\rho$ only after having performed rule SEQ_0 , while the same process may be immediately available in the multiset in the execution from $\mathcal{K}(\mathbf{ta}\rho)$. This is why we only obtain a weak execution $\mathcal{K}(\mathbf{ta}\rho) \xRightarrow{\mathbf{ta}\rho} (\mathcal{P}''; \phi)$. \square

Proposition 8. *If $\mathbf{ta} = \mathbf{ta}_1.\mathbf{ta}_2$ is a well-formed annotated trace and $\mathcal{K}(\mathbf{ta}_1.\mathbf{ta}_2)\rho \xrightarrow{\mathbf{ta}_1\rho} K$ then $\mathcal{K}(\mathbf{ta}_1)\rho \xrightarrow{\mathbf{ta}_1\rho} K'$ with $\phi(K) = \phi(K')$.*

Proof. The argument is the same as for Proposition 3, item (4): the processes that are added to $\mathcal{K}(\mathbf{ta}_1)\rho$ when considering $\mathcal{K}(\mathbf{ta}_1.\mathbf{ta}_2)\rho$ are unused in the execution of $\mathbf{ta}_1\rho$; moreover, the effect of ρ on the processes of $\mathcal{K}(\mathbf{ta}_1)$ is obviously the same as in $\mathcal{K}(\mathbf{ta}_1.\mathbf{ta}_2)$. \square

Finally, after having defined the notion of *connection* between agents, we can state our key lemma.

Definition 23. *Annotations a and a' are connected in (\mathbf{ta}, ϕ) if they are associated in (\mathbf{ta}_0, ϕ) for some prefix \mathbf{ta}_0 of \mathbf{ta} that contains at least one τ_{then} action of an unsafe conditional annotated with either a or a' .*

Lemma 2. *We assume that Π satisfies frame opacity and item (i) of well-authentication. Let \mathbf{ta} be a well-formed annotated trace such that $\mathcal{K}(\mathbf{ta}) \xrightarrow{\mathbf{ta}} (\mathcal{P}; \phi)$. Let ρ be a renaming of annotations. Moreover, when $\text{fn}(\mathcal{I}) \cap \text{fn}(\mathcal{R}) \neq \emptyset$ (shared case), we assume that for any annotations a, a' , it holds that a and a' are connected in (\mathbf{ta}, ϕ) , if, and only if, $\rho(a)$ and $\rho(a')$ are dual.*

We have that $\mathcal{K}(\mathbf{ta})\rho \xrightarrow{\mathbf{ta}\rho} (\mathcal{Q}; \psi)$ for some ψ such that $\phi \sim \psi$.

Proof. For any prefix $\mathcal{K}(\mathbf{ta}) \xrightarrow{\mathbf{ta}_0} (\mathcal{P}_0; \phi_0)$ of the execution $\mathcal{K}(\mathbf{ta}) \xrightarrow{\mathbf{ta}} (\mathcal{P}; \phi)$, we prove that there exists an execution $\mathcal{K}(\mathbf{ta})\rho \xrightarrow{\mathbf{ta}_0\rho} (\mathcal{Q}_0; \psi_0)$ with those invariants:

- (a) $\mathcal{P}_0 \mp \mathcal{Q}_0$, *i.e.* $\mathcal{P}_0 = \{\bigsqcup_{j \in \mathcal{J}} P_j^i[a_j^i]\}_{i \in \mathcal{I}}$, and $\mathcal{Q}_0 = \{\bigsqcup_{j \in \mathcal{J}} Q_j^i[\rho(a_j^i)]\}_{i \in \mathcal{I}}$, where P_j^i and Q_j^i are equal up to terms (*i.e.* ignoring terms in outputs and conditionals);

- (b) $\phi_0 \sim \psi_0$;
- (c₁) when $fn(\mathcal{I}) \cap fn(\mathcal{R}) = \emptyset$ (non-shared case), $\rho(a)$ and $\rho(a')$ are associated in $(\mathbf{ta}_0\rho, \psi_0)$ if, and only if, a and a' are associated in (\mathbf{ta}_0, ϕ_0) ;
- (c₂) when $fn(\mathcal{I}) \cap fn(\mathcal{R}) \neq \emptyset$ (shared case), $\rho(a)$ and $\rho(a')$ are associated in $(\mathbf{ta}_0\rho, \psi_0)$ if, and only if, a and a' are associated in (\mathbf{ta}_0, ϕ_0) and connected in (\mathbf{ta}, ϕ) .

We proceed by induction on the prefix \mathbf{ta}_0 of \mathbf{ta} .

Case \mathbf{ta}_0 is empty. In such a case, $\mathbf{ta}_0\rho$ can obviously be executed, and condition (a) holds because $\mathcal{K}(\mathbf{ta}) \neq \mathcal{K}(\mathbf{ta})\rho$ by definition. Condition (b) is trivial since both frames are empty. In order to check conditions (c₁) and (c₂), note that association coincides with duality for empty traces. We start by establishing condition (c₁). Being dual simply means being distinct roles, hence one obviously has that $\rho(a)$ and $\rho(a')$ are dual if, and only if, a and a' are. This allows us to conclude for condition (c₁). Now, we establish condition (c₂). By hypothesis, we have that a and a' are connected in (\mathbf{ta}, ϕ) if, and only if, $\rho(a)$ and $\rho(a')$ are dual, this allows us to conclude regarding one direction. Now, if $\rho(a)$ and $\rho(a')$ are dual, then a and a' are dual too by definition of an agent renaming. Hence, we have the other direction.

Case the prefix of \mathbf{ta} is of the form $\mathbf{ta}_0.\alpha$. The action α may be an input, an output, a conditional (i.e. τ_{then} or τ_{else}) or a τ action produced by the SEQ₀ rule. By (a), we know that there is a process in \mathcal{Q}_0 which is able to perform an action of the same nature. If this action is τ (excluding the cases of $\tau_{\text{then}}, \tau_{\text{else}}$) then triggering the process in \mathcal{Q}_0 producing τ concludes the proof since all invariants are trivially preserved after this action.

We now have to deal with the case where α is an input, an output or a conditional. In those cases α is necessarily annotated, say by a , and has been produced by a process annotated a in \mathcal{P}_0 . By induction hypothesis we have $(\mathcal{P}_0; \phi_0)$ and $(\mathcal{Q}_0; \psi_0)$ and the following executions

$$\mathcal{K}(\mathbf{ta}) \xrightarrow{\mathbf{ta}_0} (\mathcal{P}_0; \phi_0) \xrightarrow{\alpha[a]} (\mathcal{P}'_0; \phi'_0) \text{ and } \mathcal{K}(\mathbf{ta})\rho \xrightarrow{\mathbf{ta}_0\rho} (\mathcal{Q}_0; \psi_0)$$

satisfying all our invariants. Note that one has $(\mathbf{ta}_0.\alpha[a])\rho = (\mathbf{ta}_0\rho).\alpha[\rho(a)]$. Now, we have to prove that exactly the same action α can be executed by the corresponding process annotated $\rho(a)$ in \mathcal{Q}_0 given by the invariant $\mathcal{P}_0 \neq \mathcal{Q}_0$ (taking into account recipe for input and failure/success for conditional), and that our invariants are preserved after its execution.

Case where α is an output. We immediately have that \mathcal{Q}_0 can perform $\alpha[\rho(a)]$, on the same channel and with the same handle. We now have to check our invariants for $\mathbf{ta}_0.\alpha[a]$. Condition (a) is obviously preserved. Conditions (c₁) and (c₂) follow from the fact that association is not affected by the execution of an output: $\rho(a)$ and $\rho(a')$ are associated in $(\mathbf{ta}_0.\alpha[a])\rho$ if, and only if, they are associated in $\mathbf{ta}_0\rho$, and similarly without ρ . Finally, we shall prove (b): $\phi'_0 \sim \psi'_0$ where ϕ'_0 (resp. ψ'_0) is the resulting frame after the action $\alpha[a]$ (resp. $\alpha[a\rho]$). Applying Proposition 3 item (4) on the execution before renaming and Proposition 8 on the execution after renaming, one obtains

$$\mathcal{K}(\mathbf{ta}_0.\alpha[a]) \xrightarrow{\mathbf{ta}_0.\alpha[a]} (\mathcal{P}''_0; \phi''_0) \text{ and } \mathcal{K}(\mathbf{ta}_0.\alpha[a])\rho \xrightarrow{(\mathbf{ta}_0\rho).\alpha[a\rho]} (\mathcal{Q}'_0; \psi'_0).$$

We finally conclude $\phi'_0 \sim \psi'_0$ using Proposition 7 on the execution on the right and then Proposition 6.

Case where α is a conditional. We first need to make sure that the outcome of the test is the same for a and $a\rho$. We let τ_x (resp. τ_y) be the action produced by evaluating the conditional of a (resp. $a\rho$) and shall prove that $\tau_x = \tau_y$. We distinguish two cases depending on whether the conditional is safe or not.

- If the conditional is safe, then its outcome only depends on the inputs and outputs of a that are statically equivalent to those of $\rho(a)$ by the invariant (b). Hence, the outcome of that test is the same for a and $\rho(a)$ and $\tau_x = \tau_y$.
- If the conditional is unsafe, we make use of Proposition 4 to show that the outcome of the conditional is the same on both sides. First, we deduce the following executions from Proposition 3 item (4) applied on the execution before renaming and Proposition 8 applied on the execution after renaming:

$$\mathcal{K}(\mathbf{ta}_0.\tau_x[a]) \xrightarrow{\mathbf{ta}_0.\tau_x[a]} (\mathcal{P}_0''; \phi_0) \text{ and } \mathcal{K}(\mathbf{ta}_0.\tau_y[a])\rho \xrightarrow{(\mathbf{ta}_0\rho).\tau_y[a\rho]} (\mathcal{Q}_0'; \psi_0).$$

To infer $\tau_x = \tau_y$ from Proposition 4, it remains to prove that a and a' are associated in (\mathbf{ta}_0, ϕ_0) if, and only if, $\rho(a)$ and $\rho(a')$ are associated in $(\mathbf{ta}_0\rho, \psi_0)$. When $fn(\mathcal{I}) \cap fn(\mathcal{R}) = \emptyset$ (non-shared case), this is given by the invariant (c₁). Otherwise, when $fn(\mathcal{I}) \cap fn(\mathcal{R}) \neq \emptyset$ (shared case), (c₂) gives us that $\rho(a)$ and $\rho(a')$ are associated in $(\mathbf{ta}_0\rho, \psi_0)$ if, and only if, a and a' are associated in (\mathbf{ta}_0, ϕ_0) and connected in (\mathbf{ta}, ϕ) . Therefore, to conclude, it is actually sufficient to show that if a and a' are associated in (\mathbf{ta}_0, ϕ_0) then $\rho(a)$ and $\rho(a')$ are associated in $(\mathbf{ta}_0\rho, \psi_0)$. Since a and a' are associated in (\mathbf{ta}_0, ϕ_0) , thanks to Proposition 4, we know that the outcome of the test will be positive (*i.e.* $\tau_x = \tau_{\text{then}}$), and thus a and a' are connected in $(\mathbf{ta}_0.\tau_{\text{then}}, \phi_0)$, and therefore a and a' are also connected in (\mathbf{ta}, ϕ) . Thanks to (c₂) we have that $\rho(a)$ and $\rho(a')$ are associated in $(\mathbf{ta}_0\rho, \psi_0)$, and we are done.

After the execution of this conditional producing $\tau_x = \tau_y$, condition (a) obviously still holds since $\tau_x = \tau_y$ implying that both agents go to the same branch of the conditional. Invariant (b) is trivial since frames have not changed. Conditions (c₁) and (c₂) are preserved because the association between a and a' is preserved if, and only if, the outcome of the test is positive, which is the same before and after the renaming.

Case where α is an input. We immediately have that \mathcal{Q}_0 can perform $\alpha[\rho(a)]$ on the same channel and with the same recipe (since $dom(\phi_0) = dom(\psi_0)$ follows from $\phi_0 \sim \psi_0$). Conditions (a) and (b) are obviously preserved. Conditions (c₁) and (c₂) are preserved because honest interactions are preserved by the renaming, since $\phi_0 \sim \psi_0$ by invariant (b). We only detail one direction of (c₁), the other cases being similar. Assume that $\rho(a)$ and $\rho(a')$ are associated in $((\mathbf{ta}_0.\alpha[a])\rho, \psi_0)$. The renamed agents $\rho(a)$ and $\rho(a')$ are also associated in $(\mathbf{ta}_0\rho, \phi')$, thus a and a' are associated in (\mathbf{ta}_0, ϕ') . Now, because α did not break the association of $\rho(a)$ and $\rho(a')$ in $(\mathbf{ta}_0\rho, \psi_0)$, it must be that the input message in $\alpha = \text{in}(c, M)$ corresponds to the last output of $\rho(a')$ in $\mathbf{ta}_0\rho$. Formally, if that last output corresponds to the handle w in ψ_0 , we have $M\psi_0 \Downarrow_{=E} w\psi_0$. But, because $\phi_0 \sim \psi_0$ by invariant (b), we then also have $M\phi_0 \Downarrow_{=E} w\phi_0$ and the association of a and a' in (\mathbf{ta}_0, ϕ_0) carries over to $(\mathbf{ta}_0.\alpha[a], \phi_0)$. \square

E. Final proof

Thanks to Lemma 2, we can transform any execution of $\mathcal{M}_{\Pi, \bar{id}}$ into an indistinguishable execution of \mathcal{S}_{Π} , provided that an appropriate renaming of annotations exists. In order to prove that such a renaming exists in Proposition 10, we show below that in the shared case, agents cannot be connected multiple times.

Proposition 9. *Assume that Π satisfies item (ii) of well-authentication and that $fn(\mathcal{I}) \cap fn(\mathcal{R}) \neq \emptyset$ (shared case). Consider a well-formed annotated trace \mathbf{ta} and an execution $\mathcal{K}(\mathbf{ta}) \xrightarrow{\mathbf{ta}} (\mathcal{P}; \phi)$. Let a , a_1 , and a_2 be three annotations such that a and a_1 (resp. a and a_2) are connected in (\mathbf{ta}, ϕ) , then we have that $a_1 = a_2$.*

Proof. Consider the first unsafe conditional performed in \mathbf{ta} by one of the three agents a , a_1 or a_2 . This conditional exists and must be successful, otherwise the agents would not be connected in \mathbf{ta} . In other words, we have $\mathbf{ta} = \mathbf{ta}' \cdot \tau_{\text{then}}[x] \cdot \mathbf{ta}''$ where $x \in \{a, a_1, a_2\}$ and \mathbf{ta}' does not contain any unsafe conditional performed by one of our three agents. Since a is connected with both a_1 and a_2 in \mathbf{ta} , it is associated with both a_1 and a_2 in \mathbf{ta}' . This contradicts condition (ii) of well-authentication applied to $\mathbf{ta}' \cdot \tau_{\text{then}}[x]$. \square

Proposition 10. *Let Π be a protocol satisfying item (ii) of well-authentication, and \mathbf{ta} be a well-formed annotated trace such that $\mathcal{K}(\mathbf{ta}) \xrightarrow{\mathbf{ta}} K$. There exists a renaming of annotations ρ such that:*

- $\mathbf{ta}\rho$ is single-session;
- Moreover, when $fn(\mathcal{I}) \cap fn(\mathcal{R}) \neq \emptyset$ (shared case), for any annotations a and a' , we have that a and a' are connected in (\mathbf{ta}, ϕ) , if, and only if, $\rho(a)$ and $\rho(a')$ are dual.

Proof. For $\bar{k} \in \text{id}_I(\mathbf{ta}) \cup \text{id}_R(\mathbf{ta})$, we define $\text{Co}(\bar{k})$ as follows:

- when $fn(\mathcal{I}) \cap fn(\mathcal{R}) = \emptyset$ (non-shared case), we let $\text{Co}(\bar{k})$ be the empty set.
- when $fn(\mathcal{I}) \cap fn(\mathcal{R}) \neq \emptyset$ (shared case), we let $\text{Co}(\bar{k})$ be the set of all (\bar{n}_1, \bar{n}_2) such that $I(\bar{k}, \bar{n}_1)$ and $R(\bar{k}, \bar{n}_2)$ are connected in $(\mathbf{ta}, \phi(K))$;

Essentially, $\text{Co}(\bar{k})$ denotes the set of pairs of (dual) sessions that the renaming to be defined should keep on the same identity. Applying Proposition 9, we deduce that for any $\bar{k} \in \text{id}_A(\mathbf{ta})$ and $(\bar{n}_1, \bar{n}_2), (\bar{n}_3, \bar{n}_4) \in \text{Co}(\bar{k})$, then either (i) $\bar{n}_1 = \bar{n}_3$ and $\bar{n}_2 = \bar{n}_4$ or (ii) $\bar{n}_1 \neq \bar{n}_3$ and $\bar{n}_2 \neq \bar{n}_4$.

Next, we assume the existence of a function $k^c : \mathcal{N}^* \times \mathcal{N}^* \times \mathcal{N}^* \mapsto \mathcal{N}^*$ that associates to any sequence of names $(\bar{k}, \bar{n}_1, \bar{n}_2)$ a vector of names of the length of identity parameters of Π : $\bar{k}' = k^c(\bar{k}, \bar{n}_1, \bar{n}_2)$. These name vectors are assumed to be all disjoint and not containing any name already occurring in the annotations of \mathbf{ta} . This gives us a mean to pick fresh identity parameters for each combination of $\bar{k}, \bar{n}_1, \bar{n}_2$ taken from the annotations of \mathbf{ta} . We also assume a function k^1 such that the vectors $k^1(\bar{k}, \bar{n}_1)$ are again disjoint and not overlapping with annotations of \mathbf{ta} and any $k^c(\bar{k}', \bar{n}_1', \bar{n}_2')$, and similarly for $k^2(\bar{k}, \bar{n}_2)$ which should also not overlap with k^1 vectors. These last two collections of identity parameters will be used to give fresh identities to initiator

and responder agents, independently. We then define ρ as follows:

$$\begin{aligned} I(\bar{k}, \bar{n}_1) &\mapsto I(k^c(\bar{k}, \bar{n}_1, \bar{n}_2), \bar{n}_1) && \text{if } (\bar{n}_1, \bar{n}_2) \in \text{Co}(\bar{k}) \\ &\mapsto I(k^1(\bar{k}, \bar{n}_1), \bar{n}_1) && \text{otherwise} \\ R(\bar{k}, \bar{n}_2) &\mapsto R(k^c(\bar{k}, \bar{n}_1, \bar{n}_2), \bar{n}_2) && \text{if } (\bar{n}_1, \bar{n}_2) \in \text{Co}(\bar{k}) \\ &\mapsto R(k^2(\bar{k}, \bar{n}_2), \bar{n}_2) && \text{otherwise} \end{aligned}$$

We now prove that the renaming ρ defined above satisfies all requirements.

The mapping ρ is a renaming. First, for any well-formed \mathbf{ta}' , the fact that $\mathbf{ta}'\rho$ is well-formed follows from the following: (i) session names are not modified and (ii) identity names are all pairwise distinct and never intersect except for agents $\rho(I(\bar{k}, \bar{n}_1))$ and $\rho(R(\bar{k}, \bar{n}_2))$ such that $(\bar{n}_1, \bar{n}_2) \in \text{Co}(\bar{k})$ but there cannot be a third agent sharing the same identity names according to the result obtained above. The mapping ρ is obviously role-preserving. Finally, if $\rho(a)$ and $\rho(a')$ share the same identity parameters then (a) $\text{fn}(\mathcal{I}) \cap \text{fn}(\mathcal{R}) \neq \emptyset$ and (b) a and a' are connected in (\mathbf{ta}, ϕ) and are thus dual implying that a and a' share the same identity parameters as well.

The renaming ρ is single-session. First, id_0 never occurs in the image of ρ . Second, all agents are mapped to agents having fresh, distinct identity parameters except for agents a, a' that were connected in (\mathbf{ta}, ϕ) . However, as already discussed, in such a case, there is no third agent sharing those identity parameters and a and a' are necessarily dual.

To conclude, we shall prove that, in the shared case, for any annotations a, a' , it holds that a and a' are connected in (\mathbf{ta}, ϕ) , if, and only if, $\rho(a)$ and $\rho(a')$ are dual. This is actually a direct consequence of the definition of the renaming ρ . \square

We are now able to prove our main theorem.

Proof of Theorem 1. We have that $\mathcal{S}_\Pi \sqsubseteq \mathcal{M}_\Pi \sqsubseteq \mathcal{M}_{\Pi, \bar{i}\bar{d}}$, and we have to establish that $\mathcal{M}_{\Pi, \bar{i}\bar{d}} \sqsubseteq \mathcal{S}_\Pi$. Consider an execution $\mathcal{M}_{\Pi, \bar{i}\bar{d}} \xrightarrow{\mathbf{ta}} (\mathcal{P}; \phi)$. First, thanks to Proposition 3, there is an annotated trace $\mathbf{ta}' \stackrel{\tau}{\equiv} \mathbf{ta}$ such that $\mathcal{K}(\mathbf{ta}) \xrightarrow{\mathbf{ta}'} (\mathcal{P}', \phi)$. Let ρ be the renaming obtained in Proposition 10 for \mathbf{ta}' . By Lemma 2, we have that $\mathcal{K}(\mathbf{ta})\rho \xrightarrow{\mathbf{ta}'\rho} (\mathcal{Q}; \phi_\rho)$ for some frame ϕ_ρ such that $\phi_\rho \sim \phi$. We then deduce from Proposition 7 that $\mathcal{K}(\mathbf{ta}\rho) \xrightarrow{\mathbf{ta}'\rho} (\mathcal{Q}'; \phi_\rho)$, and thus $\mathcal{K}(\mathbf{ta}\rho) \xrightarrow{\mathbf{ta}\rho} (\mathcal{Q}'; \phi_\rho)$. Since $\mathbf{ta}\rho$ is single-session, Proposition 3 implies that $(\mathcal{S}_\Pi; \emptyset) \xrightarrow{\mathbf{ta}\rho} (\mathcal{Q}''; \phi_\rho)$, and this allows us to conclude. \square