Verifying unlinkability, the case of stateful protocols

David BAELDE, Stéphanie DELAUNE, Solène MOREAU

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Verifying unlinkability, the case of stateful protocols

verifying

- using formal methods in the symbolic model
- automatic tools
Verifying unlinkability, the case of stateful protocols

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- using **formal methods** in the **symbolic model**
- **automatic tools**

unlinkability

- "the real system is indistinguishable from an ideal system"
- expressed as an **equivalence-based** property: $\mathcal{M}_\Pi \approx S_\Pi$
- for an **unbounded** number of sessions
Verifying unlinkability, the case of stateful protocols

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unlinkability

- "the real system is indistinguishable from an ideal system"
- expressed as an equivalence-based property: $M_\Pi \approx S_\Pi$
- for an unbounded number of sessions

the case of stateful protocols

- protocols requiring to maintain a global, non-monotonic state
- authentication protocols with tags, reader and database
A challenging problem

- verifying **equivalence-based** properties on protocols is difficult
  - unbounded case: undecidable in general [Chrétien 2016]
  - bounded case: tools scale badly

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\(^1\) ProVerif, Tamarin
A challenging problem

- verifying **equivalence-based** properties on protocols is difficult
  - unbounded case: undecidable in general [Chrétien 2016]
  - bounded case: tools scale badly

- existing tools \(^1\) implement a procedure to check equivalence in the unbounded case
  - based on a **strong notion of equivalence** (diff-equivalence)
  - no termination guarantee
  - other limitations: states, XOR, etc

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\(^1\) ProVerif, Tamarin
Related work on unlinkability - CSF’10

2010 23rd IEEE Computer Security Foundations Symposium

Analysing Unlinkability and Anonymity Using the Applied Pi Calculus

Myrto Arapinis, Tom Chothia, Eike Ritter and Mark Ryan

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Abstract—An attacker that can identify messages as coming from the same source, can use this information to build up a picture of targets’ behaviour, and so, threaten their privacy. In response to this danger, unlinkable protocols aim to make it impossible for a third party to identify two runs of a protocol as coming from the same device. We present a framework for analysing unlinkability and anonymity in the applied pi calculus. We show that unlinkability and anonymity are complementary properties; one does not imply the other. Using our framework we show that the French RFID e-passport preserves anonymity but it is linkable therefore anyone carrying a French e-passport can be physically traced.

→ "proof" of unlinkability for UK e-passport protocol (but false)
Related work on unlinkability - CSF’10

Formal verification of privacy for RFID systems

Mayla Brusó, Konstantinos Chatzikokolakis, and Jerry den Hartog
Eindhoven University of Technology

Abstract. RFID tags are being widely employed in a variety of applications, ranging from barcode replacement to electronic passports. Their extensive use, however, in combination with their wireless nature, introduces privacy concerns as a tag could leak information about the owner’s behaviour. In this paper we define two privacy notions, untraceability and forward privacy, using a formal model based on the applied π calculus, and we show the relationship between them. Then we focus on a generic class of simple privacy protocols, giving sufficient and necessary conditions for untraceability and forward privacy for this class. These conditions are based on the concept of frame independence that we develop in this paper. Finally, we apply our techniques to two identification protocols, formally proving their privacy guarantees.

→ proof of unlinkability for OSK protocol and Basic Hash protocol (but only for the tag)
Related work on unlinkability - CCS’12

New Privacy Issues in Mobile Telephony: Fix and Verification

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ABSTRACT
Mobile telephony equipment is daily carried by billions of subscribers everywhere they go. Avoiding linkability of subscribers by third parties, and protecting the privacy of those subscribers is one of the goals of mobile telecommunication protocols. We use formal methods to model and analyse the security properties of 3G protocols. We expose two novel threats to the user privacy in 3G telephony systems, which make it possible to trace and identify mobile telephony subscribers, and we demonstrate the feasibility of a low cost implementation of these attacks. We propose fixes to these

→ proof of unlinkability for AKA protocol (but simplified)
A Method for Verifying Privacy-Type Properties: The Unbounded Case

Lucca Hirschi, David Baelde and Stéphanie Delaune
LSV, CNRS & ENS Cachan, Université Paris-Saclay, France

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 one 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, corresponding to data and control-flow leaks.

This theoretical result is general enough to apply to a wide class of protocols. In particular, we apply our techniques to provide the first formal security proof of the BAC protocol (e-passport). 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) and one on the PACE protocol (e-passport).

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 [3]. 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 [4]. 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 [5], the Tamarin prover [6], and the ProVerif tool [7].

Unfortunately, most of these results and tools focus on sufficient conditions for unlinkability (but stateless protocols)
Outline of the talk

Example-driven discussion
  OSK protocol
  Basic Hash protocol
  LAK protocol

Theory

Case studies

Conclusion
Example-driven discussion
Figure 1: Description of the OSK protocol [Ohkubo et al. 2003]
OSK protocol

Figure 2: Unlinkability attack for the OSK protocol
• proof of unlinkability in [Brusò et al. 2010]$^2$, but only for the tag

$^2$CSF’10 "Formal Verification of Privacy for RFID Systems"
OSK protocol

- proof of unlinkability in [Brusò et al. 2010]², but only for the tag
  - definition of unlinkability requiring "that the attacker cannot distinguish whether two interfaces correspond to the same tag or two different tags"

²CSF’10 "Formal Verification of Privacy for RFID Systems"
OSK protocol

- proof of unlinkability in [Brusò et al. 2010][2], but **only for the tag**
  - **definition of unlinkability** requiring "that the attacker cannot distinguish whether two interfaces correspond to the same tag or two different tags"
  - in this analysis, **Reader process is explicitly set to 0**

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[2] CSF’10 "Formal Verification of Privacy for RFID Systems"
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Keypoint #1
Modelling the reader is important.

²CSF’10 "Formal Verification of Privacy for RFID Systems"
Basic Hash protocol

Figure 3: Description of the Basic Hash protocol [Weis et al. 2004]
Basic Hash protocol

Figure 4: With specific readers, unlinkability attack
Basic Hash protocol

Figure 5: With a generic reader, no unlinkability attack
Basic Hash protocol

- specific readers can be realistic / helpful
  - for example: e-passport
- on our examples, considering a generic reader with a database is more realistic
Basic Hash protocol

• specific readers can be realistic / helpful
  • for example: e-passport

• on our examples, considering a generic reader with a database is more realistic

Keypoint #2
The way the reader is modelled is important.
Figure 6: Description of the LAK protocol, replacing XOR by pairs
LAK protocol

Figure 7: Unlinkability attack for the LAK protocol (with pairs)
LAK protocol

- stateless version of the LAK protocol (with pairs) proved unlinkable [Hirschi et al. 2016]³
- but updating a state can introduce observables

³SP’16 "A Method for Verifying Privacy-Type Properties: The Unbounded Case"
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- but updating a state can introduce observables

**Keypoint #3**
The way the protocol handles desynchronization is important.

³SP’16 "A Method for Verifying Privacy-Type Properties: The Unbounded Case"
To take-away

Keypoint #1
Modelling the reader is important.

Keypoint #2
The way the reader is modelled is important.

Keypoint #3
The way the protocol handles desynchronisation is important.
Theory
Definition

\[ M_\Pi := ! \text{new } \overline{k}.(! \text{new } \overline{n}_T.T \mid ! \text{new } \overline{n}_R.R) \]
\[ S_\Pi := ! \text{new } \overline{k}.(\text{new } \overline{n}_T.T \mid \text{new } \overline{n}_R.R) \]

A protocol \( \Pi \) ensures **unlinkability** if \( M_\Pi \approx S_\Pi \).
A result for stateless 2 party protocols [Hirschi et al. 2016]

Definition

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A protocol \( \Pi \) ensures **unlinkability** if \( M_\Pi \approx S_\Pi \).

Theorem

*If a protocol \( \Pi \) ensures both **well-authentication** and **frame opacity**, then \( \Pi \) ensures unlinkability.*

These 2 conditions are easier to check by existing tools.
Intuition behind the sufficient conditions

Well-Authentication
"whenever a conditional is positively evaluated, the agents involved are having so far an honest interaction"

⇒ This is a reachability property!
### Intuition behind the sufficient conditions

<table>
<thead>
<tr>
<th>Well-Authentication</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;whenever a conditional is positively evaluated, the agents involved are having so far an honest interaction&quot;</td>
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</table>

⇒ This is a reachability property!

<table>
<thead>
<tr>
<th>Frame Opacity</th>
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</thead>
<tbody>
<tr>
<td>&quot;any reachable frame must be statically equivalent to an idealised frame that only depends on data already observed during the execution&quot;</td>
</tr>
</tbody>
</table>

⇒ This can be verified with (an extension of) diff-equivalence.
Extending this result to stateful protocols

Definition

\( M_\Pi := (\! \text{new } \overline{k}. \ i \ \text{new } \overline{n}_T.T) \ | \ ! (\text{new } \overline{n}_R.\mathcal{R} + \text{DB}) \)

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A protocol \( \Pi \) ensures **unlinkability** if \( M_\Pi \approx S_\Pi \).

**Theorem**

*If a protocol \( \Pi \) ensures well-authentication, frame opacity and **no desynchronization** then \( \Pi \) ensures unlinkability.*
Intuition behind no desynchronization

No desynchronization

"an honest interaction between a tag and a reader cannot fail"

⇒ This is also a reachability property! (But a little more tricky...)
No desynchronization

"an honest interaction between a tag and a reader cannot fail"

⇒ This is also a reachability property! (But a little more tricky...)

Attacks on OSK and LAK protocols
There exists an execution where an honest interaction goes into the else branch (because the tag and the reader are desynchronized).
Case studies
## Case studies: checking conditions with Tamarin

<table>
<thead>
<tr>
<th></th>
<th>unlinkability</th>
<th>WA</th>
<th>FO</th>
<th>ND</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Basic Hash Protocol</strong></td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
</tr>
<tr>
<td><strong>Hash-Lock Protocol</strong></td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
<td>ok</td>
</tr>
<tr>
<td><strong>OSK</strong></td>
<td>attack</td>
<td>ok</td>
<td>?</td>
<td>X</td>
</tr>
<tr>
<td><strong>LAK (pairs)</strong></td>
<td>attack</td>
<td>ok</td>
<td>?</td>
<td>X</td>
</tr>
<tr>
<td><strong>LAK (pairs) fixed</strong></td>
<td>?</td>
<td>ok</td>
<td>?</td>
<td>ok</td>
</tr>
<tr>
<td><strong>AKA</strong></td>
<td>?</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

ok = property holds  
X = property does not hold  
? = property not yet checked, work in progress
Conclusion
To take-away

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- related work: **not yet successful stories** for stateful protocols in the symbolic model for an unbounded number of sessions
Verifying unlinkability, the case of stateful protocols

- related work: not yet successful stories for stateful protocols in the symbolic model for an unbounded number of sessions

Our contribution

- a model and definition of unlinkability taking into account some keypoints
  - importance of modeling the reader, and how it is modelled
  - states can introduce observables, especially in the case of a desynchronization
- extending a result to stateful protocols by defining a new sufficient condition also simpler to verify by existing tools
- case studies (Basic Hash, Hash-Lock, OSK, LAK, AKA, ?)
Ongoing and future work

**Frame opacity** "any reachable frame must be statically equivalent to an idealised frame that only depends on data already observed during the execution"

- simple property in the theory but **not so easily checkable** in practice
- **diff-equivalence too strong** regarding conditionals in idealized frames
  - with simple idealizations, over-approximating the set of traces is sound
  - with more complex idealizations, this is not the case anymore
- we would like to tell Tamarin to **forget about previously outputted messages**
Thank you! Any questions?
**Figure 8:** Description of the LAK protocol, replacing XOR by pairs
LAK protocol

- **in the specification:** the reader with state $h^n(k)$ accepts an honest message from a tag with state $h^n(k)$ or $h^{n-1}(k) \Rightarrow$ handles desynchronization of only one step

- **a possible fix:** the reader with state $h^n(k)$ accepts any honest message from a tag with state $h^m(k)$, where $m \leq n \Rightarrow$ handles desynchronization of many steps