Proving physical proximity using symbolic models

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2018-07-08

Introduction

Cryptographic protocols

Distributed programs that use cryptographic primitives to ensure security properties.

secrecy authentication

integrity

untraceability

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Cryptographic protocols

Distributed programs that use cryptographic primitives to ensure security properties.

secrecy authentication

integrity

untraceability

physical proximity

Example: Brands and Chaum - 1993

V_0 $(\mathsf{pk}(P))$ | P $(\mathsf{sk}(P))$

`new` m, k

$$\xleftarrow{\quad commit(m, k) \quad}$$

`new` b

$$\xrightarrow{\quad b \quad}$$

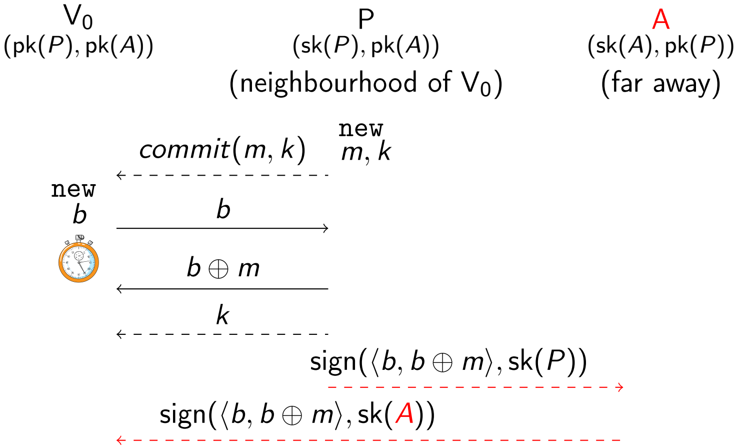
$$\xleftarrow{\quad b \oplus m \quad}$$

$$\xleftarrow{\quad k \quad}$$

$$\xleftarrow{\quad \mathsf{sign}(\langle b, b \oplus m \rangle, \mathsf{sk}(P)) \quad}$$

Brands and Chaum protocol

Example: Brands and Chaum - 1993

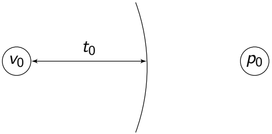


Attack against Brands and Chaum protocol

Classes of attacks

Mafia frauds - $\mathcal{C}_{\mathbf{MF}}$
(or Man-in-the-Middle)

- V_0 is honest
- P_0 is honest



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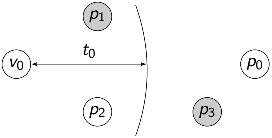

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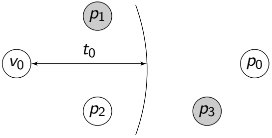

Distance hijacking - $\mathcal{C}_{\mathsf{DH}}$

- V_0 is honest
- P_0 is **dishonest**
- no dishonest agents close to V_0

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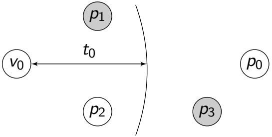

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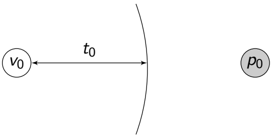

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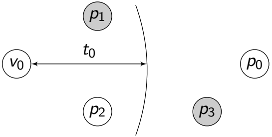

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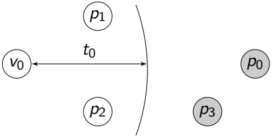
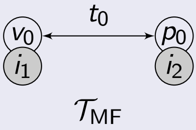
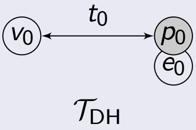


Contributions

Reduction results

Consider 1 topology is enough to prove Mafia fraud or Distance hijacking resistance!





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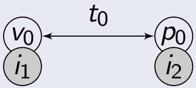
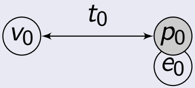


$\mathcal{T}_{\mathsf{MF}}$



$\mathcal{T}_{\mathsf{DH}}$

Getting rid of topologies and time

- modelling in ProVerif using phases
- application to well-known DB protocols

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Symbolic verification

Advantages:

- automated proofs
- efficient tools exist: **ProVerif**, Tamarin, Avispa...
- can express many security properties (authentication, secrecy, untraceability...)

But: cannot express physical proximity !
omniscient and ubiquitous attacker

How can we handle it?

Term algebra

Messages: terms built over a set of names $\mathcal{N}$ and a signature Σ given with either an equational theory E or a rewriting system

Example

- Names: $\mathcal{N} = \{a, n, k\}$
- Signature: $\Sigma = \{senc, sdec, pair, proj_1, proj_2, \oplus\}$

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

$$sdec(senc(x, y), y) \to x \qquad proj_1(pair(x, y)) \to x$$
$$proj_2(pair(x, y)) \to y$$

We have that: $sdec(senc(n \oplus 0), k), k)\!\downarrow\; =_{\mathsf{xor}} n$

Process algebra

The role of an agent is described by a process following the grammar:

$$\begin{array}{lcll} P & := & 0 & \text{null} \\ & \mid & \mathtt{new}\ n.P & \text{name restriction} \\ & \mid & \mathtt{let}\ x = u\ \mathtt{in}\ P & \text{conditional declaration} \\ & \mid & \mathtt{out}(u).P & \text{output} \\ & \mid & \mathtt{in}(x).P & \text{input} \end{array}$$

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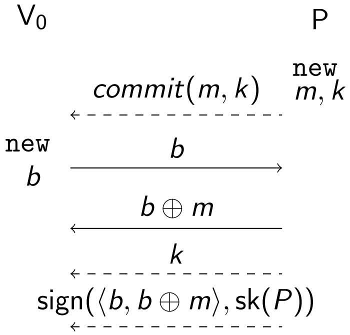
Protocol

A protocol is a set of roles $(\Pi_1, \cdots, \Pi_k)$ describing the behaviour of each honest agents.

Example: Brands and Chaum - 1993



Brands and Chaum

Example: Brands and Chaum - 1993

$$
\begin{aligned}
&V(z_V, z_P) := \\
&\quad \mathtt{in}(y_c).\mathtt{new}\ b. \\
&\quad \mathtt{reset}.\mathtt{out}(b).\mathtt{in}^{<2\times t_0}(y_0). \\
&\quad \mathtt{in}(y_k).\mathtt{in}(y_{\mathsf{sign}}). \\
&\quad \mathtt{let}\ y_m = \mathsf{open}(y_c, y_k)\ \mathtt{in} \\
&\quad \mathtt{let}\ y_{msg} = \mathsf{getmsg}(y_{\mathsf{sign}})\ \mathtt{in} \\
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&\quad 0
\end{aligned}
$$

V_0 | P

P: $\mathtt{new}$ m, k

$V_0 \xleftarrow{commit(m, k)} P$

V_0: $\mathtt{new}$ b

$V_0 \xrightarrow{b} P$

$V_0 \xleftarrow{b \oplus m} P$

$V_0 \xleftarrow{k} P$

$V_0 \xleftarrow{\mathsf{sign}(\langle b, b \oplus m\rangle, \mathsf{sk}(P))} P$

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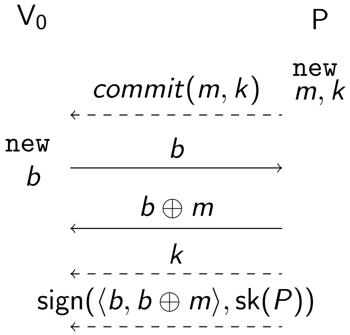

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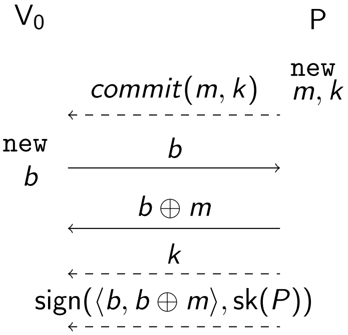
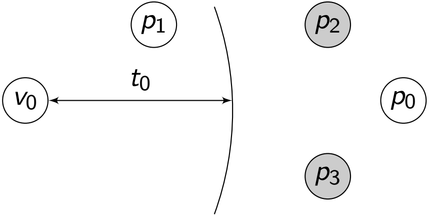


Brands and Chaum

Topology

A **topology** is a tuple $\mathcal{T} = (\mathcal{A}, \mathrm{Loc}, \mathcal{M}, v_0, p_0)$.



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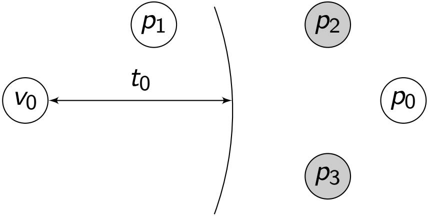
agents



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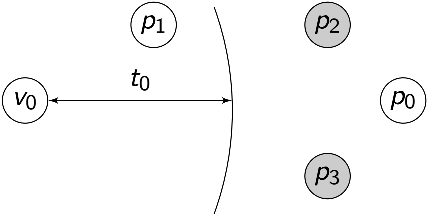

We define $\mathrm{Dist}_{\mathcal{T}}(a, b) = \frac{\|\mathrm{Loc}(a) - \mathrm{Loc}(b)\|}{c}$

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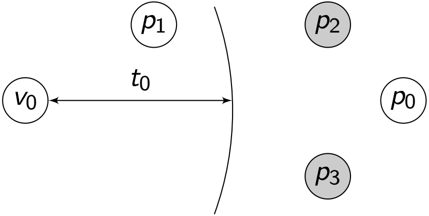
agents

locations

dishonest agents



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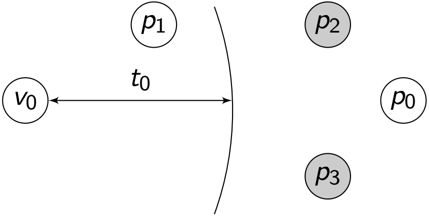
agents
locations
dishonest agents
specific agents



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Configuration and semantics

A **configuration** is a tuple $(\mathcal{P}; \Phi; t)$ where:

- $\mathcal{P}$ is a multiset of $\lfloor P \rfloor_a^{t_a}$ with $a \in \mathcal{A}$ and $t_a \in \mathcal{R}_+$
- $\Phi = \{\mathrm{w}_1 \xrightarrow{a_1, t_1} m_1, \cdots, \mathrm{w}_n \xrightarrow{a_n, t_n} m_n\}$ is a frame
- $t \in \mathcal{R}_+$ is the global time

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OUT $\quad (\lfloor \mathtt{out}(u).P \rfloor_a^{t_a}) \uplus \mathcal{P}; \Phi; t) \xrightarrow{a, \mathtt{out}(u)}_{\mathcal{T}_0} (\lfloor P \rfloor_a^{t_a} \uplus \mathcal{P}; \Phi'; t)$
with $\Phi' = \Phi \cup \{\mathrm{w} \xrightarrow{a,t} u\}$

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if u is deducible from Φ

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if $\exists b \in \mathcal{A}, t_b \in \mathcal{R}_+$ such that $t_b \leq t - \mathsf{Dist}_{\mathcal{T}}(b, a)$ and:

- if $b \notin \mathcal{M}$ then $u \in img(\lfloor \Phi \rfloor_b^{t_b})$
- if $b \in \mathcal{M}$ then u is deducible from $\bigcup_{c \in \mathcal{A}} \lfloor \Phi \rfloor_c^{t_b - \mathsf{Dist}_{\mathcal{T}}(c,b)}$

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Moreover if $\star =< t_g$ then $t_a < t_g$.

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TIME $\quad (\mathcal{P}; \Phi; t) \longrightarrow_{\mathcal{T}} (\mathcal{P}'; \Phi; t')$ with:

- $t' > t$
- $\mathcal{P}' = \{ \lfloor P \rfloor_a^{t_a + (t' - t)} \mid \lfloor P \rfloor_a^{t_a} \in \mathcal{P} \}$

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NEW, LET, RST $\quad \ldots$

Security property: physical proximity

t_0-proximity

A protocol $\mathcal{P}_{prox}$ ensures t_0-proximity w.r.t. a topology $\mathcal{T} = (\mathcal{A}, \mathsf{Loc}, \mathcal{M}, v_0, p_0)$ and a configuration K if:

$$K \xrightarrow{tr}_{\mathcal{T}} (\lfloor \mathsf{end}(v_0, p_0) \rfloor_{v_0}^{t_{v_0}}; \Phi; t) \Rightarrow \mathsf{Dist}_{\mathcal{T}}(v_0, p_0) < t_0.$$

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Mafia frauds (resp. Distance hijacking attacks)

A protocol $\mathcal{P}_{prox}$ is resistant against Mafia frauds (resp. Distance hijacking attacks) if for all topologies $\mathcal{T} \in \mathcal{C}_{\mathrm{MF}}$ (resp. $\mathcal{C}_{\mathrm{DH}}$) and initial configurations K:

$$K \xrightarrow{tr}_{\mathcal{T}} (\lfloor \mathrm{end}(v_0, p_0) \rfloor_{v_0}^{t_{v_0}}; \Phi; t) \Rightarrow \mathrm{Dist}_{\mathcal{T}}(v_0, p_0) < t_0.$$

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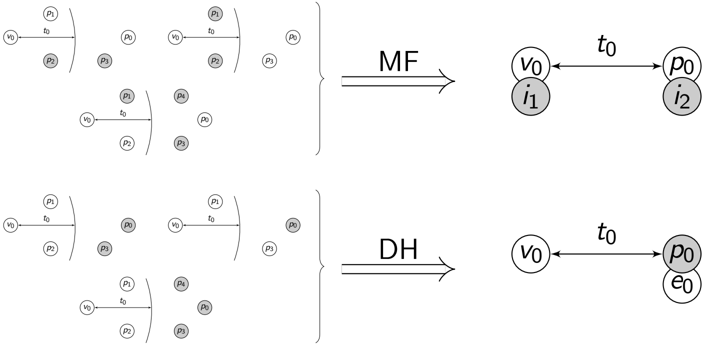
Reduction results

Only one topology is sufficient !

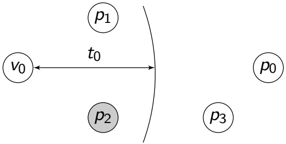


Mafia fraud attacks

Theorem

Let $\mathcal{P}_{prox}$ be an **executable** protocol.
$\mathcal{P}_{\mathsf{prox}}$ admits a Mafia fraud attack w.r.t. t_0-proximity, if and only if, there is an attack against t_0-proximity in the topology $\mathcal{T}_{\mathsf{MF}}$.

Sketch of proof:



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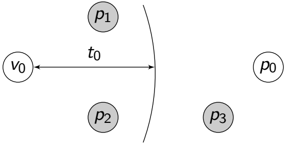

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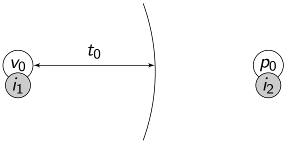
2. we place them ideally [Nigam *et. al.*, 16]



Mafia fraud attacks

Theorem

Let $\mathcal{P}_{prox}$ be an **executable** protocol.
$\mathcal{P}_{\mathrm{prox}}$ admits a Mafia fraud attack w.r.t. t_0-proximity, if and only if, there is an attack against t_0-proximity in the topology $\mathcal{T}_{\mathrm{MF}}$.

Sketch of proof:

1. the honest agents become malicious –> no executed processes
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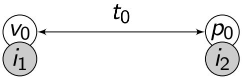

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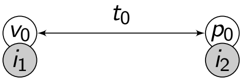


Remark. This proof cannot be adapted for distance hijacking attacks !

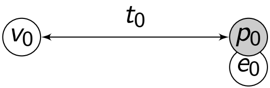
Distance hijacking attacks

Theorem

Let $\mathcal{P}_{prox}$ be a protocol such that the Verifier role respects the following grammar:

$$\begin{array}{rcl|l|l} P, Q := & \mathtt{end}(z_0, z_1) & \mathtt{in}(x).P & \mathtt{let}\ x = v\ \mathtt{in}\ P \\ | & \mathtt{new}\ n.P & \mathtt{out}(u).P & \mathtt{reset.out}(u').\mathtt{in}^{<t}(x).P \end{array}$$

If $\mathcal{P}_{\mathrm{prox}}$ admits a Distance hijacking attack w.r.t. t_0-proximity, then $\overline{\mathcal{P}_{\mathrm{prox}}}$ admits an attack against t_0-proximity in the topology $\mathcal{T}_{\mathrm{DH}}$.



$\mathcal{T}_{\mathrm{DH}}$

In $\overline{\mathcal{P}_{\mathrm{prox}}}$ we only keep guards computed by v_0.

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ProVerif [Blanchet, 01]

ProVerif is a verifier tool for cryptographic protocols.

http://proverif.inria.fr/

- fully automated proofs
- handles an unbounded number of sessions
- can model protocols defined by phases (*e.g.* e-voting)
  - $\rightarrow$ $(\texttt{phase}\ i).P$ represents a process P that can only be executed in phase i

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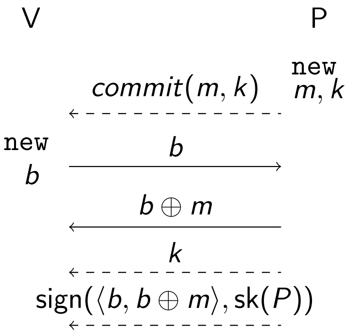
Phases in DB protocols:

- Phase 0 $\rightarrow$ slow initialisation phase
- Phase 1 $\rightarrow$ rapid phase
- Phase 2 $\rightarrow$ slow verification phase

Translation into ProVerif

$\mathit{Transf}(\mathcal{T}, \mathcal{P}, t_0)$

$$
\begin{array}{l}
V_0(v_0, p_0) := \\
\quad \texttt{in}(y_c).\texttt{new}\ b. \\
\quad \texttt{reset}.\texttt{out}(b).\texttt{in}^{<2\times t_0}(y_0). \\
\quad \texttt{in}(y_k).\texttt{in}(y_{\mathsf{sign}}). \\
\quad \texttt{let}\ y_m = \mathsf{open}(y_c, y_k)\ \texttt{in} \\
\quad \texttt{let}\ y_{msg} = \mathsf{getmsg}(y_{\mathsf{sign}})\ \texttt{in} \\
\quad \texttt{let}\ y_{\mathsf{check}} = \mathsf{check}(y_{\mathsf{sign}}, \mathsf{vk}(z_P))\ \texttt{in} \\
\quad \texttt{let}\ y_{\mathsf{eq}} = \mathsf{eq}(\langle b, b \oplus y_m\rangle, y_{msg})\ \texttt{in} \\
\quad \mathsf{end}(z_V, z_P). \\
\quad 0
\end{array}
$$



Brands and Chaum

Translation into ProVerif
$\mathit{Transf}(\mathcal{T}, \mathcal{P}, t_0)$

$\overline{V_0}(v_0, p_0) :=$
$\quad \mathtt{in}(y_c).\mathtt{new}\ b.$
$\quad \mathtt{phase}\ 1.$
$\quad \mathtt{out}(b).\mathtt{in}(y_0).$
$\quad \mathtt{phase}\ 2.$
$\quad \mathtt{in}(y_k).\mathtt{in}(y_{\mathsf{sign}}).$
$\quad \mathtt{let}\ y_m = \mathsf{open}(y_c, y_k)\ \mathtt{in}$
$\quad \mathtt{let}\ y_{msg} = \mathsf{getmsg}(y_{\mathsf{sign}})\ \mathtt{in}$
$\quad \mathtt{let}\ y_{\mathsf{check}} = \mathsf{check}(y_{\mathsf{sign}}, \mathsf{vk}(z_P))\ \mathtt{in}$
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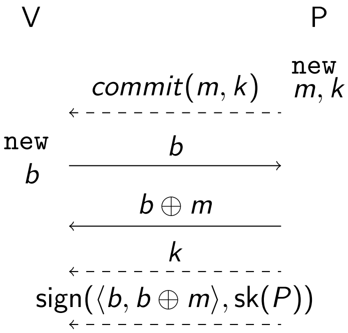


Brands and Chaum

Translation into ProVerif $Transf(\mathcal{T}, \mathcal{P}_{\text{prox}}, t_0)$

Given a process P we define:

- $P^{<}$: all the possible ways of spitting P in the phases 0, 1 and 2
- $P^{\geq}$: all the possible ways of spitting P in the phases 0 and 2

$Transf(\mathcal{T}, \mathcal{P}, t_{\text{prox}})$ is the multiset of processes derived from $\mathcal{P}$ when applying:

- $\cdot^{<}$ for all instantiated roles of $\mathcal{P}$ executed by agents close to v_0
- $\cdot^{\geq}$ for all instantiated roles of $\mathcal{P}$ executed by agents far from v_0

Proposition

If $(\mathcal{P}_{\text{prox}} \cup V_0)$ admits an attack w.r.t. t_0-proximity in $\mathcal{T}$ then $(Transf(\mathcal{T}, \mathcal{P}, t_0) \uplus \overline{V_0}(v_0, p_0); \Phi_{init}; 0)$ admits an attack in ProVerif.

Case analysis - DB protocols

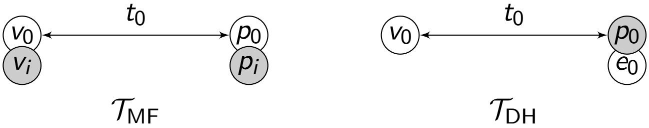
Protocols	MF	DH
Brands and Chaum	✓	×
Meadows *et al.* $(n_V \oplus n_P, P)$	✓	✓
Meadows *et al.* $(n_V, n_P \oplus P)$	✓	×
TREAD-Asymmetric	×	×
TREAD-Symmetric	✓	×
MAD (One-Way)	✓	×
Swiss-Knife	✓	✓
Munilla *et al.*	✓	✓
CRCS	✓	×
Hancke and Kuhn	✓	✓

(×: attack found, ✓: proved secure)
Coherent with the formal analysis recently done by Mauw *et. al.* using Tamarin

Conclusion

We have adapted the standard applied Pi-Calculus to take into account time and locations.

We obtained **two reduction results** that reduce the number of relevant topologies that need to be studied to only 2.



We provide a solution to prove t_0-proximity using a **usual verification tool**, ProVerif, and we applied it to analyse well-known protocols.

Future work

⇒ Define a more precise notion of time.

⇒ Take into account **Terrorist frauds**:

Terrorist frauds

A remote dishonest prover cooperates with another dishonest agent, close to the verifier, to authenticates himself to the prover without giving any advantages for future attacks.