

Comparing State Spaces in Automatic Security Protocol Verification *

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Abstract. Many tools exist for automatic security protocol verification, and most of them have their own particular language for specifying protocols and properties. Several protocol specification models and security properties have been already formally related to each other. However, there is an important difference between verification tools, which has not been investigated in depth before: the explored state space. Some tools explore all possible behaviors, whereas others explore strict subsets, often by using so-called scenarios. Ignoring such differences can lead to wrong interpretations of the output of a tool. We relate the explored state spaces to each other and find previously unreported differences between the various approaches.

We apply our study of state space relations in a performance comparison of several well-known automatic tools for security protocol verification. We model a set of protocols and their properties as homogeneously as possible for each tool. We analyze the performance of the tools over comparable state spaces. This work enables us to effectively compare these automatic tools, i.e. using the same protocol description and exploring the same state space. We also propose some explanations for our experimental results, leading to a better understanding of the tools.

1 Introduction

Cryptographic protocols form an essential ingredient of current network communications. These protocols use cryptographic primitives to ensure secure communications over insecure networks. The networks are insecure in two ways: there can be attackers analyzing or influencing network traffic, and communication partners might be either dishonest or compromised by an attacker. Despite the relatively small size of the protocols it is very difficult to design them correctly,

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and their analysis is complex. The canonical example is the famous Needham-Schroeder protocol [31], that was proven secure by using a formalism called BAN logic. Seventeen years later G. Lowe [26], found a flaw by using an automatic tool known as Casper/FDR. The flaw was not detected in the original proof because of different assumptions on the intruder model. However, the fact that this new attack had escaped the attention of the experts was an indication of the underestimation of the complexity of protocol analysis. This example has shown that automatic verification is critical for assessing the security of such cryptographic protocols, because humans can not reasonably verify their correctness.

A few years later it was proven that the security problem is in fact undecidable [1, 23] even for restricted cases (see e.g. [19] for a survey). This inherent undecidability is one of the major challenges for automatic verification. For instance, in the tool used by Lowe, undecidability was addressed by restricting the type of protocol behaviours that were explored. The protocol that Lowe investigated has two roles, and these may be performed any number of times, by an unbounded number of agents. Lowe used his tool to check a very specific setup, known as a *scenario*. Instead of exploring all possible protocol behaviours, the protocol model given to the tool considers a very small subset, in which there are only a few instances of each role. Furthermore, the initiator role is always performed by a different agent than the responder role. The attack that Lowe found fits exactly in this scenario. However, if there would have been an attack that requires the intruder to exploit two instances of the responder role, Lowe would not have found this particular attack with the tool. Addressing this problem, he managed to give a manual proof for the repaired version of the protocol, which states that if there exists any attack on that protocol, then there exists an attack within the scenario. Ideally, we would not need such manual proofs, and explore the full state space of the protocol, or at least a significant portion of it.

Since then, many automatic tools based on formal analysis techniques have been presented for the verification of cryptographic protocols [2, 7, 12, 13, 18, 20, 28–30, 33, 34]. These tools address undecidability in different ways: either by restricting the protocol behaviours similar to the approach used by Lowe, or by using abstraction methods. However the restrictions put on the protocol behaviour are rarely discussed or compared to the related work. Moreover, the tools provide very different mechanisms to implicitly restrict the protocol behaviours, and the relations between these mechanisms has not been investigated yet.

This work started out as an investigation into the relative performance of protocol verification tools. Given the number of security protocol verification tools, it is rather surprising that there exists hardly any comparison studies between different tools. In each tool paper the authors propose some tests about their tools' efficiency, by describing the performance of the tool for a set of protocols. These tests implicitly use behaviour restrictions, which are often not specified and sometimes are designed specifically to include known attacks on the tested protocols. Choosing different restrictions has a very clear impact on the accuracy as well as the performance of verification process. In particular, imposing

stronger restrictions on the protocol behaviour implies that fewer behaviours need to be explored, which means that for most tools verification time will be exponentially lower.

Here we address two distinct, but very closely related problems. First, we discuss types of behaviour restriction models used by protocol verification tools, which we will also refer to as the explored *state space*. We show how these different state spaces are related to finding, or missing, attacks on protocols, and show how to match up certain state space types. Second, we use the knowledge gained about state spaces to perform a tool performance case study, where we try to match up the exact restrictions used in each tool, and compare their performance on similar state spaces. This leads to new insights in the performance of the tools.

Related work To the best of our knowledge, the difference between state spaces in security protocol analysis has not investigated before. However, some work exists on comparing the performance of different security protocol analysis tools.

In [36], a large set of protocols is verified using the Avispa tool suite [2] and timing results are given. As the Avispa tool suite consists of four back end tools, this effectively works as a comparison between these four tools. However, this test does not detail the behavioural restrictions that were used. Furthermore, no conclusions about the results are drawn.

A qualitative comparison between Avispa and Hermes [13] is presented in [24]. Unfortunately this test is not very detailed and leads only to some general advice for users of these two tools.

We conjecture that tests as performed here, have not been done before because of the amount of work involved in setting up comparable test cases, and the amount of detailed knowledge required for using each tool. In fact, we believe that a number of researchers in this field have neglected to compare their work with other tools, at any deeper level than just citing from publications.

Outline In Section 2 we describe and relate some of the different state spaces considered in protocol analysis. In Section 3 we present our performance comparison experiments. We describe the choice of tools and test setup. We then discuss the results of the analysis before we move to the conclusions and future work in the last section.

2 State spaces in security protocol analysis

2.1 Process model

We first give a high-level description of the protocol verification problem in terms of processes. It is not our intent to go into full detail but only to provide the required knowledge for understanding the state space restrictions in the remainder of this paper. For further details we refer the reader to e.g. [20].

A security protocol is defined as a set of communicating processes, typically called “roles”. Any of these roles can be performed any number of times in parallel. A role usually consists of a sequence of send and receive events, and implicit or explicit generation of fresh values such as nonces or session keys. The network is considered to be insecure. This is modeled as a single “intruder” named e and represented by the process q . She can take messages from the network, manipulate them, insert messages into the network, or generate fresh values.

We introduce some notation for describing composition of processes. We write $P||Q$ to denote the parallel composition of processes P and Q . We denote by P^* the parallel composition of any number of P processes, i.e. $P^* = P||P||P||\dots$. Using this notation, the full protocol system describing a protocol with two roles ($r1, r2$) and the intruder process is given by $q||r1^*||r2^*$. This system exhibits all possible behaviours of the protocol in presence of an active intruder.

For basic security properties such as authentication and secrecy we can define behaviours of the system as all possible execution traces. We denote the set of all possible traces of the protocol as *Traces*. If there exists an attack on the abstract protocol, it is represented in this set. Conversely, if no trace in *Traces* exhibits an attack, there is no attack on the abstract protocol.

2.2 Restricting the state space

Because of undecidability or efficiency concerns, protocol analysis tools usually apply some restrictions on the system and do not explore all elements from the set *Traces*.

Definition 1. *Terminology.*

- A run is a single (possibly partial) instance of a role, performed by an agent (this notion is known under various names in protocol models, e.g. “regular strand”, “process”, or “thread”).
- A run description of a protocol with $|R|$ roles is a set of roles. An element of a run description is of the form $r(a_1, a_2, \dots, a_{|R|})$, where r denotes the role that the run is performing. The parameters a_x denote the assignment of agents a_x to each role x . A symbolic run description contains variables, whereas a concrete run description does not contain variables.
- A Scenario is a multiset of run descriptions. \mathcal{S} denotes the set of all possible scenarios and \mathcal{S}_c the set of concrete scenarios in which no variables occur.

Alternatively, one may view a run description as a process that performs a particular role and in which the choice of agents (both the executing agent and the expected communication partners) is explicitly encoded by the parameters. A trace of a protocol is an interleaving of runs and (possibly) intruder events.

Example 1. The concrete scenario $\{r1(a, e), r2(a, b)\}$ for the Needham-Schroeder protocol exhibits the man-in-the-middle attack. The first process is an initiator run (denoted by $r1$), performed by a , talking to a compromised agent e . The

second process is a responder run ($r2$), performed by b , who thinks he is talking to a . Note that the same attack occurs when we substitute a by b . In fact, the attack exists for the following symbolic scenario $\{r1(X, e), r2(X, Y)\}$. Note that both scenarios above do not cover the following scenario: $\{r1(a, e), r1(a, b)\}$ which corresponds to two runs that are *both* performing the initiator role. In particular, there are traces in the second scenario that are not in the third scenario, and vice versa. Thus, if we evaluate the second scenario, we might get completely different results than with the third scenario.

2.3 State space classes

A restriction on the behaviour of a process model changes its state space. Thus, we can view a protocol behaviour restriction as a representation of exploring an alternative state space for the protocol. We identify a set of possible state spaces representing classes of protocol behaviour restrictions.

Definition 2. *Let n be an integer, and let s be a scenario.*

- *Traces is the set of all traces (possible executions of the protocol) of any length, and any combination of agents.*
- *MaxRuns(n) is the set of traces with at most n runs.*
- *Scenario(s) is the set of traces with at most the runs defined in the scenario s . Thus, the multiset of runs in each trace are by definition a subset of s .*
- *RepScen(s) is the set of traces built only with runs that are present in s . The runs defined by the scenario s can be executed any number of times. In other words, each run in each trace corresponds to an element of s .*

Each restriction above effectively restricts the state space of a process model. When we talk about the correctness of a protocol, we refer to the full set of possible behaviours, denoted by Traces. As we will see in Section 3, most tools do not cover this set.

2.4 Relations between state space restrictions

For the set of scenarios \mathcal{S} , we have the following relations:

$$\forall n \in \mathbb{N} : \text{MaxRuns}(n) \subset \text{Traces} \quad (1)$$

$$\forall s \in \mathcal{S} : \text{Scenario}(s) \subset \text{Traces} \quad (2)$$

$$\forall s \in \mathcal{S} : \text{RepScen}(s) \subseteq \text{Traces} \quad (3)$$

$$\exists s \in \mathcal{S} : \text{RepScen}(s) = \text{Traces} \quad (4)$$

Proof. The relations (1), (2) and (3) above are immediate consequences of the definitions, as the left hand sides imply restrictions on the full set Traces. For relation (4) we have that if the scenario s includes all possible process descriptions, the repetition of the processes in s effectively amounts to the full set of behaviours without any restrictions.

We write $|s|$ to denote the number of elements of the scenario s . Relating the scenario-based approaches to the bounding of runs, we have that:

$$\forall s \in \mathcal{S} : \text{Scenario}(s) \subseteq \text{MaxRuns}(|s|) \quad (5)$$

Observe that if the scenario contains $|s|$ runs, the resulting traces will never contain more, and thus this included in $\text{MaxRuns}(|s|)$.

The next formula expresses that there exist no concrete scenarios that correspond exactly to a MaxRuns trace set.

$$\forall n \in \mathbb{N}^*, s \in \mathcal{S}_c : \text{Scenario}(s) \neq \text{MaxRuns}(n) \quad (6)$$

Proof. For any $n > 0$, $\text{MaxRuns}(n)$ contains a trace with n runs. So, it will also contain a trace containing n instances of the first role, and also a trace containing n instances of the second role. To match $\text{MaxRuns}(n)$ to $\text{Scenario}(s)$, s must also contain exactly n runs. Because we are considering only concrete scenarios, we need to define in s the first case (n times the first role). However, by this definition of s we have excluded the second type of traces with only the second role.

Furthermore, under the assumption that we have a finite number of agents we have that

$$\forall n \in \mathbb{N}, \exists k : \exists s_1, \dots, s_k \in \mathcal{S}_c : \bigcup_{i=1}^k \text{Scenario}(s_i) = \text{MaxRuns}(n) \quad (7)$$

The last formula expresses that if we have finite agents, we can simply enumerate all possible run descriptions of n runs, and turn them into scenario sets. The result of this formula is that we can match up the trace sets of MaxRuns and Scenario by unfolding. This opens up a way to make the state spaces uniform.

2.5 Generation of uniform state spaces

Starting from a state space described using $\text{MaxRuns}(n)$ for an integer n , we generate a set of concrete scenarios that exactly covers the same state space, by using Formula (7). Further parameters involved in the generation of this set of scenarios are the number of roles of the protocol and the number of agents.

Required number of agents In protocol verification it is common to use two honest agents and a single untrusted (compromised) agent. In general, attacks might require more agents, depending on the protocol under investigation and the exact property one wants to verify. A number of results related to this can be found with proofs in [17]. We recall the results of this paper that we use here:

- Only a single dishonest (compromised) agent e , is enough.
- For the verification of secrecy, only a single honest agent a is sufficient.

- For the verification of authentication, we only need two honest agents a and b .

For example, for a single honest agent a and a single compromised agent e , for a protocol with roles $\{r1, r2\}$, we have that:

$$\text{MaxRuns}(1) = \left(\bigcup_{k \in \{a, e\}} \text{Scenario}(\{r1(a, k)\}) \right) \cup \left(\bigcup_{k \in \{a, e\}} \text{Scenario}(\{r2(k, a)\}) \right)$$

yielding a set of four scenarios.

Computing the minimal number of concrete scenarios For a given integer n , we can derive the minimal size of a set M of concrete scenarios, such that $\bigcup_{s \in M} s = \text{MaxRuns}(n)$. This minimal size of M directly corresponds to determining the minimal value of k in Formula (7).

For a single agent (involved in the verification of secrecy), the generation of a set of concrete scenarios is a trivial application of the binomial coefficient. For two agents or more the situation is not so simple. In particular, the generation of the set is complicated by the fact that the scenario sets are considered equivalent up to renaming of the honest agents.

Example 2 (Renaming equivalence). Let P be a protocol with a single role $r1$. Consider the state space $\text{MaxRuns}(2)$ for two honest agents a, b . Then, we could generate the following scenario set:

$$\{ \{r1(a), r1(a)\}, \{r1(a), r1(b)\}, \{r1(b), r1(b)\} \}$$

However, as the names of the honest agents are interchangeable, the last scenario is equivalent up to renaming to the first one. In order to verify security properties, we would need only to consider the first two scenarios.

We generalize this approach by considering $|R|$ roles in the protocol description. we assume that we have two agents a and b and one intruder. Let n be the parameter of $\text{MaxRuns}(n)$ for which we want to generate the equivalent set of scenarios. In order to choose a run description $X(a_1, \dots, a_{|R|})$, we have $|R|$ choices for the role X , two choices for a_1 a or b and 3 possible values: a , b or the attacker for each $a_2, \dots, a_{|R|}$, and we find there are $2 * |R| * 3^{(|R|-1)}$ different possible run descriptions. Now we have to choose a multiset of n run descriptions among this set of all possible runs descriptions. We use the following formula:

$$\binom{2 * |R| * 3^{(|R|-1)} + n - 1}{n}$$

However, this does not take into account that scenarios are equal up to the renaming of the (honest) agents. For example, we observe that $\{r1(a, b), r2(b, a)\}$ is equivalent to $\{r1(b, a), r2(a, b)\}$ under the renaming $\{a \rightarrow b, b \rightarrow a\}$.

We now use a group theory result to compute the minimal number of scenarios needed. We just recall that $\binom{n}{k} = \frac{n!}{k!(n-k)!}$ and Burnside's lemma [14].

Lemma 1 (Burnside’s lemma). *Let G be a finite group that acts on a set X . For each g in G let X^g denote the set of elements in X that are fixed by g . Then the number of orbits, denoted $|X/G|$, is:*

$$|X/G| = \frac{1}{|G|} \sum_{g \in G} |X^g|$$

where $|X|$ denotes the cardinality of the set X .

Thus the number of orbits (a natural number or infinity) is equal to the average number of points fixed by an element of G (which consequently is also a natural number or infinity). A simple proof of this lemma was proposed by Bogard [10].

We have to consider all the renamings and compute the number of scenarios that are stable by this operation. Because we have only two agents, we have only two possible renamings:

1. $\{a \rightarrow a, b \rightarrow b\}$ (the trivial renaming)
2. $\{a \rightarrow b, b \rightarrow a\}$

Observe first that $|G| = 2$ because we have two renamings. In the first case, all elements are fixed so we have $\binom{2 * |R| * 3^{(|R|-1)} + n - 1}{n}$ possibilities. In the second case, the fixed elements are multisets of the size n where the terms are associated by two and of their arguments are of the form $a, x_1, \dots, x_{|R|-1}$ or $b, x_1, \dots, x_{|R|-1}$. It corresponds to choosing a multiset of $\frac{n}{2}$ elements in a set where the first parameter is fixed, i.e, in a set of cardinality $|R| * 3^{(|R|-1)}$. Notice that if n is odd the second set is empty because in this case there is no way to get a fixed element using the second renaming.

Lemma 1 leads to the following formula, where ϵ_n is 0 if n is odd and 1 otherwise. $k(n, |R|)$ is the minimal number of scenarios k for Formula (7).

$$k(n, |R|) = \frac{\binom{2 * |R| * 3^{(|R|-1)} + n - 1}{n} + \epsilon_n \binom{|R| * 3^{(|R|-1)} + \frac{n}{2} - 1}{\frac{n}{2}}}{2} \quad (8)$$

For instance for a protocol with $|R| = 2$ roles, we have that the set of traces $\text{MaxRuns}(2)$ is equal to the union of the trace sets defined by $k(2, 2) = 42$ different scenarios.¹ Note that if we would not have taken the renaming equivalence into account, we would instead generate $\binom{2 * 2 * 3^{2-1} + 2 - 1}{2} = 78$ scenarios.

2.6 Practical implications

In general, tools can explore radically different state spaces. With protocol verification, we are looking for two possible results: finding attacks on a protocol or having some assurance of the correctness of the protocol.

¹ Interested readers can inspect this scenario by running ‘Scenario.py’ in the test archive [21].

If an attack on a protocol is found, any unexplored parts of the state space are often considered of little interest. However, if one is trying to establish a level of assurance for the correctness of a protocol, the explored state space becomes of prime importance. As established in the previous section, even for two honest agents, the simplest protocols already need 42 concrete scenarios to explore exactly all attacks involving two runs.

In many cases, protocol models attempt to increase the coverage of small (i.e. involving few runs) attacks by including a scenario with a high number of runs. This process is very error prone: as an example we mention that in the Avispa modeling [4] of the TLS protocol [32] a large scenario is used in the example files, which covers many small attacks, but not scenarios in which an agent can communicate with itself. As a result, the protocol is deemed correct by the Avispa tools, whereas other tools find an attack. This is a direct result of the fact that the used scenario does not cover all attacks for even a small number of runs. One can discuss the feasibility of such an attack, and argue that an agent would not start a session with herself, but the fact remains that the protocol specification does not exclude this behaviour, and therefore certainly means that the protocol does not meet the security properties for its specification.

When one uses a tool for verification of a protocol one should be aware of the impact the state space choices have on the verification result, in order to avoid getting a false sense of security from a tool.

3 Experiments

In this section we use the state space analysis of Section 2 to perform a comparison between several tools on a set of well-known cryptographic protocols considering the same state space. We first discuss some of the choices made for these experiments, after which we give the results of the tests and discuss them.

3.1 Settings

Tool selection We have compared tools that we could freely download and for which a Linux command-line version exists. Consequently, we had to exclude some tools. In particular, we cannot confirm the results of Athena [34] and NRL [29] as these tools are not available. We do not compare Hermes [13] because the current version of the tool has only a web interface, which is unsuitable for performance testing. We also do not consider the Murphi [30] tool since the current version does not seem to be compatible with any compiler version we had available.

Consequently we have used the most recent versions of the following six tools:

Avispa (Version: 1.1) consists of the following four tools that take the same input language called HLPSL [2]:

- **CL-Atse:** (Version: 2.2-5) Constraint-Logic-based Attack Searcher applies constraint solving with simplification heuristics and redundancy elimination techniques [35].

- **OFMC:** (Version of 2006/02/13) The On-the-Fly Model-Checker employs symbolic techniques to perform protocol falsification as well as bounded verification, by exploring the state space in a demand-driven way. OFMC² implements a number of optimizations, including constraint reduction, which can be viewed as a form of partial order reduction [5].
- **Sat-MC:** (Version: 2.1, 3 April 2006) The SAT-based Model-Checker builds a propositional formula encoding all the possible traces (of bounded length) on the protocol and uses a SAT solver [3].
- **TA4SP:** (Version of Avispa 1.1) Tree Automata based on Automatic Approximations for the Analysis of Security Protocols approximates the intruder knowledge by using regular tree languages and rewriting to produce under- and overapproximations [11].

The first three Avispa tools (CL-Atse, OFMC and Sat-MC) take a concrete scenario (as required by the HLPSL language) and consider all traces of Scenario(*s*).

The last Avispa backend, TA4SP, also takes a HLPSL scenario, but verifies the state space that considers any number of repetitions of the runs defined in the scenario, yielding RepScen(*s*). TA4SP is based on overapproximations and hence might find false attacks. As no trace is ever reconstructed by TA4SP, the user has no indication of whether the output “attack” corresponds to a false or true attack. Furthermore, there is a “level” parameter that influences whether just to use the overapproximation (level = 0), or underapproximations of the overapproximation (level > 0). In the Avispa default setting only level 0 is explored by default, which in our test cases would have resulted in never finding any attacks, finding in 57% of all cases “inconclusive”, and in the remaining 43% “correct”. For our tests, we start at level 0 and increase the level parameter until it yields a result that is not “inconclusive”, or until we hit the time bound. This usage pattern is suggested both by the authors in [11] as well as by the output given by the backend when used from the Avispa tool.

ProVerif: (Version: 1.13pl8) analyzes an unbounded number of runs by using over-approximation and represents protocols by Horn clauses. ProVerif [7, 9] accepts two kind of input files: Horn clauses and a subset of the Pi-calculus. For uniformity with the other tools we choose to model protocols in the Pi-calculus.

ProVerif takes a description of a set of processes, where each defined processes can be started any number of times. The tool uses an abstraction of fresh nonce generation, enabling it perform unbounded verification for a class of protocols. When ProVerif is given a protocol description, one of four things can happen. First, the tool can report that the property is false, and will yield an attack trace. Second, the property can be proven correct.

² OFMC can also consider symbolic scenarios. However, this feature cannot be used through the common Avispa input language HLPSL, but requires changing the Intermediate Format (IF) description of the protocol. Therefore we have not considered this option here, but will do so in future extensions of this work.

Third, the tool reports that the property cannot be proved, for example when a false attack is found. Fourth, the tool might not terminate. It is possible to describe protocols in such a way that $\text{RepScen}(s)$ is correctly modeled, resulting in the exploration of Traces. Note that the examples provided with ProVerif in general do not consider Traces.

Scyther: (Version: 1.0-beta6) verifies bounded and unbounded number of runs, using a symbolic analysis with a backwards search based on (partially ordered) patterns [20].³ Scyther does not require the input of scenarios. It explores $\text{MaxRuns}(n)$ or Traces: in the first case, even for small n , it can often draw conclusions for Traces. In the second case, termination is not guaranteed.

In the default setup Scyther explores $\text{MaxRuns}(5)$, is guaranteed to terminate, and one of the following three situations can occur. First, the tool can establish that the property holds for $\text{MaxRuns}(5)$ (but not necessarily for Traces). Second, the property is false, and an attack trace is shown. Third, the property can be proven correct for Traces.

A summary of the tools and their respective state spaces is given in Table 1.

Tools	State spaces	Constraints
CL-Atse,Sat-MC,TA4SP	Scenario(s)	$s \in \mathcal{S}_c$
OFMC,ProVerif	Scenario(s)	$s \in \mathcal{S}$
Scyther	$\text{MaxRuns}(n)$, Traces	$n \in \mathbb{N}$

Table 1. State spaces explored by the tools

In order to compare the tools fairly, we match up the state spaces. As a candidate for a common state space, any unbounded set (Traces, RepScen) is not suitable. Furthermore, as Scenario can be used to simulate MaxRuns, but not the other way around, we choose MaxRuns as the common denominator of the selected tools. We automatically generate for each number of runs n the corresponding input files to perform a fair time comparison over $\text{MaxRuns}(n)$. Note that the time measurements for the tools only include their actual running times, and does not include the time needed for the generation of the input files.

Security properties In the tests we analyze secrecy of nonces and session keys, i.e. is it possible that an intruder learns a secret, as well as authentication, i.e. ensuring that an agent communicates with another agent and not with the intruder. For each of the selected tools, secrecy can be modeled. This is not the case for authentication. TA4SP cannot model authentication at all. Other tools provide support for varying notions of authentication, ranging from several forms

³ Note that one of the authors is the author of the Scyther tool. We have tried to stay as objective as possible. However, given the lack of comparative studies in this area, we feel that performing a thorough comparison like this is better than not doing it.

of agreement [27] to synchronisation [22]. As an exception, we have not modeled authentication properties for ProVerif although it supports authentication [8]. In the test archive there is a file 'proverif-authentication.txt' which gives some of the underlying reasons for this choice.

Protocol test set We consider a number of well-known protocols found in the literature [4, 15, 16, 25]. We select a set that can be modeled in all tools, which excludes protocols that use e.g. algebraic properties. We have restricted ourselves to the following four protocols : the famous Needham-Schroeder [31] using public keys, and the corrected version by Lowe [26], EKE [6] which uses symmetric and asymmetric encryption, and finally TLS [32] as an example of a larger protocol.

Final setup details With respect to verification of multiple properties, we observe that some tools can test multiple properties at once, some cannot, and some stop verification at the first property where an attack is found and therefore do not evaluate all properties. We decide to analyze just one security property at a time. Thus we create appropriate files for each tool to check each security property for each protocol.

Producing all the input files requires intimate knowledge of each tool in order to create comparable protocol descriptions. Guided by our results of the previous section, we automatically construct input files for the right scenarios for each protocol and for each tool. This involves the generation of all concrete scenarios to match the state space of a given number of runs. In such cases, we generate all scenarios (ignoring renaming equivalences) in the first phase, and filter out scenarios that are equivalent under renaming in the second phase. The resulting number of scenarios matches exactly with the theoretical number computed in the previous section. For practical purposes we use a time limit of 30 seconds for each security property considered.

All our tests can be reproduced: all used scripts and models are downloadable from [21], and we have only used freely downloadable tools and well-known protocols. The tests have been performed using an AMD Sempron 3000 processor with 1GB of ram and the Linux operating system.

3.2 Results

We used each tool to verify security properties of the selected protocols. In the first set of results we present the total verification time, which corresponds to the total time needed for verifying all the properties of each protocol, for each tool. In Figure 1, we show the time for verifying the secrecy properties of the Needham-Schroeder protocol as a function of the number of runs n of the explored $\text{MaxRuns}(n)$ state space. When a tool reaches the time limit, no conclusion can be drawn about the verification time and hence no points (and connecting lines) are displayed for such cases. For a better visualisation of the exponential behaviour of some of the tools, we use a logarithmic scale.

In Appendix A we give further comments, time results for both secrecy and authentication and the graphs obtained for the other protocols.

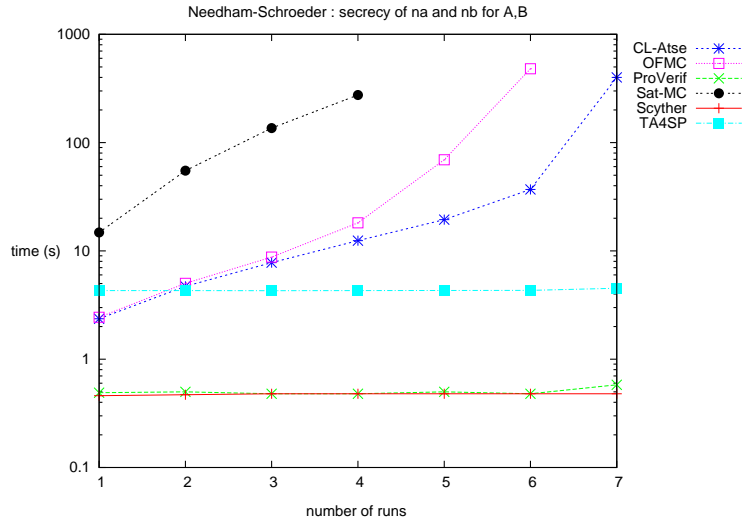


Fig. 1. Time efficiency comparison of the tools on Needham-Schroeder [31], for secrecy

This time performance analysis shows that overall, the fastest tool is ProVerif, then Scyther, TA4SP, CL-Atse, OFMC and finally Sat-MC.

- ProVerif shows the fastest performance due to abstraction of nonces. This allows the tool to obtain an efficient verification result quickly for an unbounded number of runs.
- Scyther outperforms the other bounded tools, and the fact that full verification can be achieved means that it can often achieve the same performance as tools based on abstraction methods. For some protocols, no full verification can be performed, and the tool exhibits exponential verification time with respect to the number of runs.
- The behaviour of OFMC and CL-Atse is mostly similar for the tested protocols. We observe that the curves produced by these two tools are exponential, which confirms the theoretical results for their underlying algorithms. Finally we observe that CL-Atse is somewhat faster than OFMC for higher numbers of runs.
- Sat-MC also has an exponential behaviour and is slower than CL-Atse and OFMC for lower numbers of runs. In particular, Sat-MC has proven to be especially slow for the more complex protocol TLS. In contrast, for the smaller protocols we found that Sat-MC starts slower, but its time curve is less steep than that of CL-Atse and OFMC, causing the curves to cross for particular

setups. Consequently, for some protocols and a high number of runs Sat-MC can be more efficient than CL-Atse and OFMC, which can be observed in the graphs for the EKE protocol found in the Appendix.

3.3 Discussion

During these tests we ran into many peculiarities of the selected tools. We highlight the issues we least expected.

In general, the modeling phase has proven to be time-consuming and error-prone, even though we already knew the abstract protocols well. Modeling the protocols in ProVerif took us significantly more time than for the other tools. Furthermore, in the protocol description files provided with the tool, we have not found any modeling of the famous protocol Needham-Schroeder which considers all the possible interactions between the different principals, but only examples which model some particular scenarios.

Avispa has a common input language called HLPSSL for the four backend tools. This has the benefit of allowing the user to use different tools based on a single protocol modeling. However, in HLPSSL, the link between agents and their keys is usually hard-coded in the scenarios, making the protocol descriptions unsuitable for unbounded verification, as one cannot in general predict how these links should be for further role instances (outside of the given scenario).

Even in this limited test, we found two instances where TA4SP indicates that a property of a protocol is false, where we expected the property to hold (see Appendix for details). Because no traces are produced by the tool, we are unable to investigate this further.

We realize that each of the tools has its particular strengths in other features than just performance on simple protocols. However, the focus of this research is clearly on the efficiency only. Furthermore, our tests involve only one particular efficiency measure, and there are certainly other efficiency measures (e.g. mapping all state spaces to symbolic scenarios, and many others) that we expect would lead to slightly different results. However, given that no research has ever been performed before on this topic, we see our tests as a base case for others to work from.

4 Conclusion

We have for the first time analyzed the state space models used in automatic security protocol analysis. The analysis shows the relations between the various models, revealing that protocol analysis tools actually explore by default very different state spaces. This can lead to a false sense of security, because if a tool states that no attack is found, only the explored state space is considered, and other attacks might have been missed.

Next, we match up the state spaces in order to have different tools explore similar state spaces, where we take into account that traces are considered equal up to renaming of honest agents. This leads to a result relating the number of

concrete scenarios needed to cover all traces of a protocol involving a particular number of runs.

We applied these theoretical results to a performance comparison of several automatic protocol verification tools. Rather unexpectedly, such a performance comparison has never been performed before. We modeled four well-known protocols identically for each tool, and verify the protocols using the tools on similar state spaces to obtain a fair performance comparison. The resulting scripts and data analysis programs are available from [21].

The performance results show that ProVerif is the fastest of the tools under consideration for this set of protocols, and that its approximation techniques are effective. Scyther comes in as a very close second, and has the advantage of not using approximations. CL-Atse and OFMC (with concrete sessions) are close to each other, and are the most efficient of the Avispa tools, followed by Sat-MC. For a higher number of runs of simple protocols, it seems that Sat-MC can become more efficient than the two other tools. In some cases TA4SP can complement the other Avispa tools, but in general it is significantly slower than the other tools that can handle unbounded verification (Scyther and ProVerif), and has the added drawback of not being able to show attack traces.

As future work we would like to include some other tools into the analysis, e.g. Casper/FDR [28, 33] CoProVe [18], Hermes [13], STA [12], or the symbolic sessions specification for other tools. To improve the reliability of the tests it would be interesting to investigate a wider range of protocols.

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A Detailed results

In Figure 1, we presented the performance curve obtained for verifying the secrecy properties of the Needham-Schroeder protocol for the compared tools. In this appendix we present similar graphs for Needham-Schroeder-Lowe [26], EKE [6] and TLS [32] respectively in Figure 2, 3 and 4. These results confirm the conclusions of the Needham-Schroeder example and give rise to some further observations. Because the majority of the tools exhibit exponential behaviour, we use a logarithmic scale in all these figures. We also give the full time results obtained in our tests that were used for the graph generation in Table 2.

Overview: We start our discussion of the results by presenting and analyzing the tests for secrecy for all tools. Afterwards we continue with the results for authentication for four of the six tools. Finally, we show a table which summarizes the unbounded verification performance for the tools which are able to deal with an unbounded number of runs, and the attack discovery performance for all tools.

A.1 Secrecy time results.

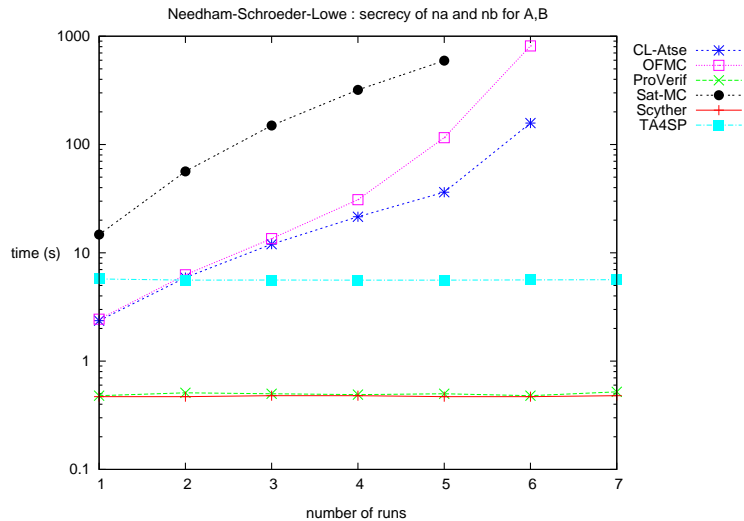


Fig. 2. Time efficiency comparison of the tools for Needham-Schroeder-Lowe [26], for secrecy

In Figure 2, one can observe (more clearly than in the Needham-Schroeder graph) that Sat-MC, OFMC and CL-Atse follow an exponential curve for the secrecy analysis of the Needham-Schroeder-Lowe protocol. Here, CL-Atse is faster

that OFMC. One other interesting point is that we can see that the curve of OFMC crosses the Sat-MC curve: in other words, for larger number of runs, Sat-MC is more efficient. This result is confirmed by the curves obtained for the EKE protocol, which we will show below. We also note that ProVerif and TA4SP have constant times. One final point to mention is that Scyther and ProVerif both show time performances of less than one second for all the security properties considered for this protocol.

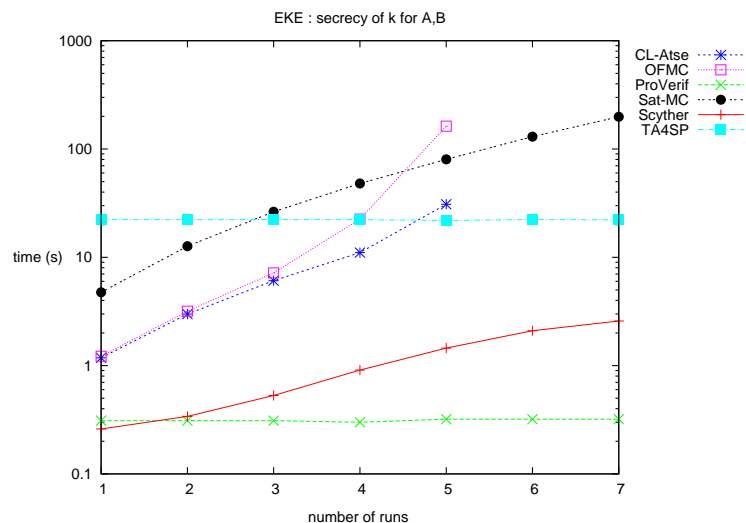


Fig. 3. Time efficiency comparison of the tools on EKE [6], for secrecy

In Figure 3, we present the efficiency result for the EKE protocol [6]. This protocol shows again that the bounded verification tools (Sat-MC, OFMC, CL-Atse) follow an exponential curve, as well as the hybrid Scyther, which has for this particular protocol also an exponential curve, albeit with much lower times than the other bounded tools. We also observe that Sat-MC has a slower exponential curve than OFMC and CL-Atse. ProVerif is still constant. We also notice that TA4SP has a constant analysis time but with a high time computation even for one process. This is due to the modeling of the protocol and to the fact that TA4SP has to construct in all cases of this protocol a complex tree automaton to perform its analysis.

The last protocol analyzed with respect to secrecy is presented in Figure 4. TLS [32] is a relatively complex protocol, and certainly the most complex protocol in this small test set. Hence, we expected the tools to spend some effort and time to get to a result. Our hypothesis was confirmed, as e.g. Sat-MC reaches the time limit for a fairly small state space already. In this example, as in the previous

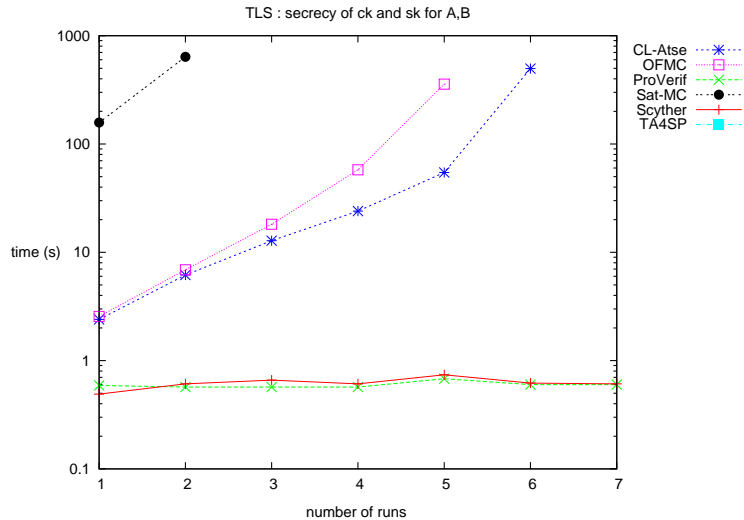


Fig. 4. Time efficiency comparison of the six tools on TLS [32], for secrecy

one (EKE), we can also see the difference between OFMC and CL-Atse, where in this example CL-Atse is faster than OFMC. This protocol also confirms the good results of Scyther which remains competitive with ProVerif and TA4SP. These three tools have all very fast time results and the variations on the curves are very small (less than 0.1 second).

Finally, in Table 2, we report the results used to construct all these graphs for the verification of secrecy. The times in this table are the sum of the times measured for each tool to verify all secrecy properties. We have fixed the time limit at 30 seconds for the computation time for the verification of a single property. For Needham-Schroeder and Needham-Schroeder-Lowe [26] we verify the four usual secrecy properties regarding the secrecy of the nonce N_a and N_b for each role, for EKE [6] only two properties concerning the secrecy of the new key for both roles, and four secrecy properties in the case of TLS [32].

A.2 Authentication time results

In this section we present the results for the tools Scyther, OFMC, Sat-MC, and CL-Atse for authentication properties of the selected protocols. We also comment on each of the graphs and give in Table 3 the time measurements that were used to construct these graphs.

In Figure 5 we analyze the performance of the verification of authentication for Needham-Schroeder. We first notice that Scyther is faster than the other

	MaxRuns	CL-Atse	OFMC	ProVerif	Sat-MC	Scyther	TA4SP
EKE	1	1.18	1.22	0.31	4.75	0.26	22.36
	2	2.99	3.18	0.31	12.67	0.34	22.22
	3	6.08	7.18	0.31	26.35	0.53	22.33
	4	11.04	22.51	0.30	48.01	0.91	22.27
	5	30.86	162.61	0.32	80.32	1.45	21.88
	6	-	-	0.32	130.24	2.10	22.33
	7	-	-	0.32	198.25	2.58	22.17
Needham-Schroeder	1	2.36	2.44	0.49	14.82	0.46	4.30
	2	4.71	5.02	0.50	55.05	0.47	4.30
	3	7.79	8.76	0.48	136.23	0.48	4.29
	4	12.42	18.16	0.48	275.21	0.48	4.30
	5	19.45	69.39	0.50	-	0.48	4.31
	6	36.92	480.93	0.48	-	0.48	4.32
	7	399.65	-	0.58	-	0.48	4.52
Needham-Schroeder-Lowe	1	2.36	2.44	0.48	14.75	0.47	5.74
	2	5.91	6.27	0.51	56.41	0.47	5.60
	3	12.01	13.52	0.50	149.69	0.48	5.61
	4	21.51	30.92	0.49	319.24	0.48	5.59
	5	36.31	115.52	0.50	595.11	0.47	5.60
	6	157.62	813.60	0.48	-	0.47	5.62
	7	-	-	0.52	-	0.48	5.64
TLS	1	2.40	2.56	0.59	157.93	0.49	-
	2	6.17	6.89	0.57	638.16	0.61	-
	3	12.81	18.15	0.57	-	0.66	-
	4	23.99	57.74	0.57	-	0.61	-
	5	54.51	357.17	0.68	-	0.74	-
	6	497.02	-	0.60	-	0.62	-
	7	-	-	0.60	-	0.61	-

Table 2. Summary of time results for secrecy (in seconds)

three tools used. We also see that CL-Atse and OFMC are very close and follow an exponential curve.

In Figure 6, we can see that the tools quickly hit the time limit, which means that the exponential curve is steeper than in the Needham-Schroeder case. We also remark that CL-Atse and OFMC are again very close. Finally we notice again that Scyther is faster than the other three used tools.

In Figure 7, we can see that the tools stop after having found an attack, which explains the flat shape for CL-Atse. In case of OFMC, there is still an exponential curve although an attack is found. We conjecture that this is caused by the specifics of the partial order reduction scheme, which effectively works like a heuristic: sometimes a non-optimal choice is made, which causes OFMC to explore a larger part of state space before the attack is found. The same explanation is valid for the smooth increasing of the Sat-MC curve towards the time limit. In this case too Scyther is the fastest one. Notice that none of the tools

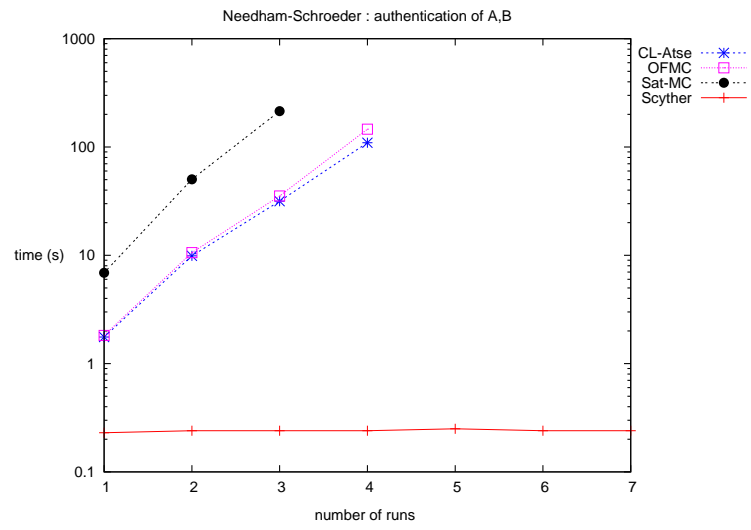


Fig. 5. Time efficiency comparison of the four tools on Needham-Schroeder [31], for authentication

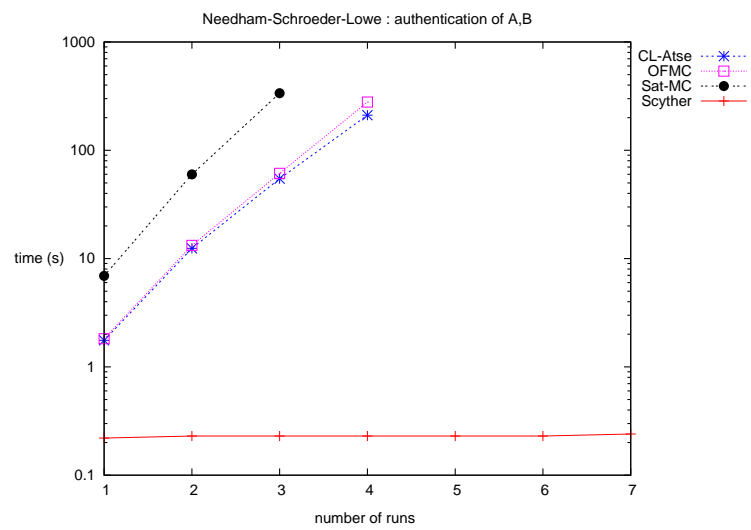


Fig. 6. Time efficiency comparison of the four tools on Needham-Schroeder-Lowe [26], for authentication

hit the time limit in this example.

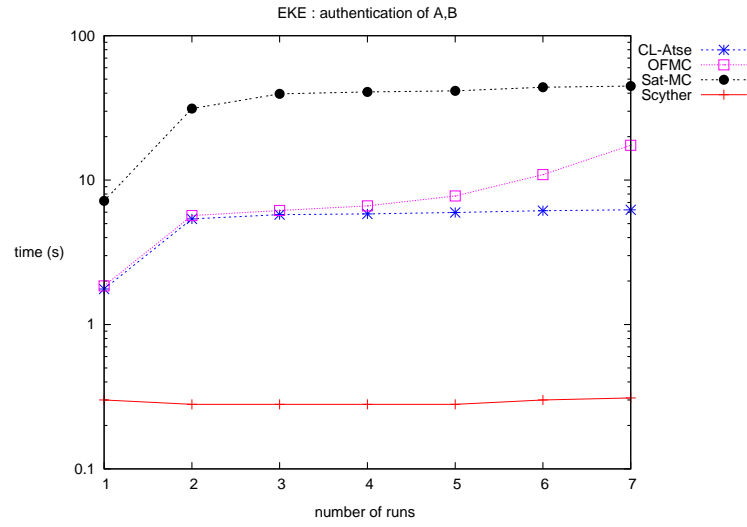


Fig. 7. Time efficiency comparison of the four tools on EKE [6], for authentication

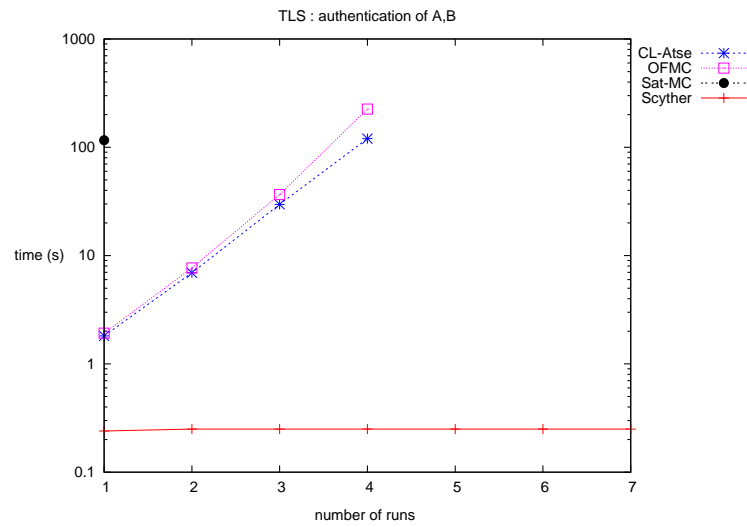


Fig. 8. Time efficiency comparison of the four tools on TLS [32], for authentication

In Figure 8, we can observe first that Scyther again is the most efficient with times of less than one second. For TLS we can see that Sat-MC reaches the time limit for the two authentication claims when analyzed for one run, but quickly

finds a flaw for state spaces with least two runs. Second we can see again the very similar time results obtained for OFMC and CL-Atse.

Finally we give the time results used for the generation of all these graphs in Table 3.

	MaxRuns	CL-Atse	OFMC	Sat-MC	Scyther
EKE	1	1.76	1.85	7.18	0.30
	2	5.39	5.68	31.27	0.28
	3	5.77	6.16	39.54	0.28
	4	5.83	6.63	40.79	0.28
	5	5.97	7.76	41.50	0.28
	6	6.14	10.91	43.97	0.30
	7	6.22	17.41	44.82	0.31
Needham-Schroeder	1	1.76	1.82	6.90	0.23
	2	9.88	10.59	50.31	0.24
	3	31.57	35.31	214.54	0.24
	4	109.43	145.96	-	0.24
	5	-	-	-	0.25
	6	-	-	-	0.24
	7	-	-	-	0.24
Needham-Schroeder-Lowe	1	1.76	1.82	6.92	0.22
	2	12.42	13.24	59.84	0.23
	3	54.73	61.24	336.21	0.23
	4	211.07	278.84	-	0.23
	5	-	-	-	0.23
	6	-	-	-	0.23
	7	-	-	-	0.24
TLS	1	1.81	1.92	116.28	0.24
	2	6.94	7.68	-	0.25
	3	29.73	36.57	-	0.25
	4	120.04	225.49	-	0.25
	5	-	-	-	0.25
	6	-	-	-	0.25
	7	-	-	-	0.25

Table 3. Summary of time results for authentication (in seconds)

A.3 Unbounded verification and attack discovery performance

In this last part we present in Table 4 a comparison of the efficiency of finding an attack by the six tools on Needham-Schroeder, for the secrecy properties. Next, we present for the tools which are able to verify protocols for an unbounded number of runs, a comparison of their efficiency for the unbounded verification of correctness of the protocol in Table 5. In both cases we discuss the results.

Comparison of attack finding efficiency We first introduce the notation used in the Table 4: “no att” means the tool finds no attack, 0.12(2!) means that the tool finds an attack in 0.12 seconds with two processes, and 0.13(1?) means that the tool finds an attack in 0.13 seconds with two processes, but it might represent a false attack.

	Secrecy	CL-Atse	OFMC	ProVerif	Sat-MC	Scyther	TA4SP
Needham-Schroeder	A na	no att	no att	no att	no att	no att	no att
	A nb	no att	no att	0.12 (1!)	no att	no att	1.44 (1?)
	B na	0.88 (2!)	0.94 (2!)	0.12 (1!)	4.35 (2!)	0.12 (2!)	0.47 (1?)
	B nb	0.88 (2!)	0.94 (2!)	0.13 (1!)	4.28 (2!)	0.12 (2!)	0.47 (1?)

Table 4. Finding an attack on Needham-Schroeder for secrecy

First we notice that ProVerif finds an attack on role *A* for the nonce *Nb*. This attack is a type flaw attack already mentioned in the literature. If we use Scyther with the specific option (–untyped), the existence of the attack is confirmed. As we use the tools with their default setting, it is expected that some tools do not find this flaw. Unfortunately we have no way of knowing what the attack found by TA4SP looks like. This is an interesting result, because according to the specification of this tool it used a typed model as dictated by the HLPSL input specification, so the type flaw attack should not occur, and we would expect TA4SP not to find an attack. However, as we have no way to extract the TA4SP “attack” we assume it is a false attack in this case.

Second we can see that with our modeling and according to the H. Common and V. Cortier result [17] which says that one honest agent is enough to prove secrecy, that ProVerif can quickly find attacks. All the other tools need two runs to find the man-in-the middle attack, as expected.

Finally we find again our conclusion about the efficiency of the tools that Scyther and ProVerif are the fastest, then TA4SP (but the status of the attacks remains unconfirmed), then CL-Atse and OFMC are second with a very small advantage to CL-Atse (which has been confirmed in the previous analysis with more runs), and finally Sat-MC.

Comparison of unbounded verification performance In this last part we analyze the performance of tools which are able to prove the correctness of a protocol. This includes Scyther, ProVerif and TA4SP, where we have considered only the secrecy properties. We perform this analysis on the four selected protocols, and detail the results in Table 5. With respect to the used notation, we mention that 0.12(3!) denotes the fact that the tool proves the correctness of the protocol with 3 runs in 0.12 seconds, *attack?* means that the tool claims to find an attack (but which we could not check), – means that there is no answer for our testing, *inconclusive* is only for TA4SP, indicating that the tool does not state anything about the property.

For TLS, TA4SP was not able to provide any answers. For EKE, Scyther could not establish unbounded verification results, and only provided bounded verification for MaxRuns(7).

	Secrecy	ProVerif	Scyther	TA4SP
EKE	A k	0.15 (1)	-	11.16 (1)
	B k	0.16 (1)	-	11.20 (1)
Needham-Schroeder	A na	0.12 (1)	0.12 (3)	1.92 (1)
	A nb	attack!	0.12 (3)	attack?
	B na	attack!	attack!	attack?
	B nb	attack!	attack!	attack?
Needham-Schroeder-Lowe	A na	0.12 (1)	0.12 (3)	1.70 (1)
	A nb	0.12 (1)	0.12 (3)	1.85 (1)
	B na	0.12 (1)	0.12 (4)	attack?
	B nb	0.12 (1)	0.12 (3)	1.71 (1)
TLS	A ck	0.15 (1)	0.16 (2)	inconclusive
	A sk	0.15 (1)	0.15 (2)	inconclusive
	B ck	0.15 (1)	0.15 (2)	inconclusive
	B sk	0.14 (1)	0.15 (2)	inconclusive

Table 5. Performance of unbounded verification