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Abstract

The configuration of firewalls is highly error prone and automated solution are needed in order to analyze its correctness. We propose a formal and automatic method for checking whether a firewall reacts correctly wrt a security policy given in an high level declarative language. When errors are detected, some feedback is returned to the user in order to correct the firewall configuration. Furthermore, the procedure verifies that no conflicts exist within the security policy. We show that our method is both correct and complete. Finally, it has been implemented in a prototype of verifier based on a satisfiability solver modulo theories (SMT). Experiment conducted on relevant case studies demonstrate the efficiency and scalability of the approach.

Keywords: security, firewall configuration, security policy, formal verification, SMT solver.

1. Introduction

Securing network flows is a crucial and difficult task. Some specific technical knowledge and clear ideas about the global security requirement to be establish are required, but are still insufficient in order to ensure the correctness of a security configuration. One of the main reasons is the difference in semantics between, on the one hand, the security policies (SP) used to express global security requirements, and on the other hand the firewall configuration files (FC). The former are generally specified in a high level declarative language and easy to understand, whereas the latter are low-level files subject to special configuration constraints in order to ensure an efficient real time processing by specific devices. One of these constraints is in particular that the filtering rules of a FC file are treated in the order in which they are read in the configuration file, in a switch-case fashion.

For instance, if two filtering rules associate different actions to the same flow type, then only the rule with the lower order is really applied. This is in contrast with the SP, which is a set of rules considered without order. In this case, the action taken, for the flow under consideration, is the one of the non executed rule.

Several methods have been proposed [12, 2, 3, 1] for the detection of inter-rule conflicts in FC. These work are limited to the problem conflict avoidance, and do not consider the more general problem of verifying whether a firewall reacts correctly wrt a given SP. Solutions are studied in [9], [6], and [10] for the analysis of firewalls’ behavior. These methods require some final user interactions by sending queries through a verification tool. Such manual solution can be tedious when checking discrepancies wrt complicated security requirements. In [4] and [8] the author address the problem of automatic verification by providing automatic translation tool of the security requirements (SP), specified in a high level language, into a set of ordered filtering rule (i.e. a FC). Therefore, these methods can handle the whole problem of conformance of FC to SP, but the validity of the compilation itself has not been proven. In particular, the FC rules obtained may be in conflict.

In this paper, we propose an automatic and generic method for checking whether a firewall is well configured wrt a security policy, given in an expressive enough declarative language. Furthermore, the proposed method ensures conflicts avoidance within the SP that we aim to establish and returns key elements for the correction of a flawed FC. Our method has been implemented as a prototype which can be used either in order to validate an existing FC wrt a given SP or downstream of a compiler of SP. It can also be used in order to assist the updates of FC, as conflicts may be created by the addition or deletion of filtering rules.

The remainder of this paper is organized as follows. Section 2 settles the definition of the problems addressed in the
paper, in particular the properties of soundness and completeness of a FC wrt SP. In Section 3, we present an inference system introducing the proposed method and prove its correctness and completeness. Section 4 elaborates our the verification procedure. Finally, in Section 5 we present an automatic verification tool that we have implemented based on our method and some experiments on a case study.

2. Soundness and Completeness Properties

The main goal of this work consists in checking whether a FC is sound and complete wrt a given SP. In this section, we define formally these notions.

We consider a finite domain \( \mathcal{P} \) containing all the headers of packets possibly incoming to or outgoing from a network. A firewall configuration (FC) is a finite sequence of filtering rules of the form \( FC = (r_i \Rightarrow A_i)_{0 \leq i < n} \). Each precondition \( r_i \) of a rule defines a filter for packets of \( \mathcal{P} \). The structure of \( r_i \) is described later in Section 5. Before, we just consider a function \( dom \) mapping each \( r_i \) into the subset of \( \mathcal{P} \) of filtered packets. Each right member \( A_i \) of a rule of FC is an action defining the behaviour of the firewall on filtered packets: \( A_i \in \{\text{accept, deny}\} \). This model describes a generic form of FC which are used by most firewall products such as Cisco, Access Control List, IPCHAINS and Check Point Firewall...

A security policy (SP) is a set \( SP \) of formulae defining whether packets are accepted or denied. The nature of the formulae is described in Section 4. In Section 3, we only consider the definition domain of \( SP \), partitioned into \( \text{dom}(SP) = \bigcup_{A \in \{\text{accept, deny}\}} SP_A. \) SP is called consistent if \( SP_{\text{accept}} \cap SP_{\text{deny}} = \emptyset \).

A FC is sound wrt a SP if the action undertaken by the firewall for each forwarding packet, (i.e. the action of the first filtering rule matching the packet) is the same as the one defined by the SP.

**Definition 1** (soundness) FC is sound wrt SP iff for all \( p \in \mathcal{P} \), if there exists a rule \( r_i \Rightarrow A_i \) in FC such that \( p \in \text{dom}(r_i) \) and for all \( j < i \), \( p \notin \text{dom}(r_j) \) then \( p \in SP_A \).

A FC is complete wrt a SP if the action defined by the firewall for each packet \( p \) is really undertaken by the firewall.

**Definition 2** (completeness) FC is complete wrt SP iff for all \( p \in \mathcal{P} \) and \( A \in \{\text{accept, deny}\} \), if \( p \in SP_A \) then there exists a rule \( r_i \Rightarrow A \) in FC such that \( p \in \text{dom}(r_i) \) \( \setminus \bigcup_{j < i} \text{dom}(r_j) \).

3 Inference System

We propose in this section necessary and sufficient condition for for the simultaneous verification of the properties of soundness and completeness of a FC wrt a SP. The conditions are presented in an inference system shown in Figure 1. The rules of the system in Figure 1 apply to couples \( (FC, D) \) whose first component \( FC \) is a sequence of filtering rules and whose second component \( D \) is a subset of \( \mathcal{P} \). This latter subset represents the accumulation of the sets of packets filtered by the rules of FC processed so far.

We write \( C \vdash_{SP} C' \) is obtained from \( C \) by application of an inference rule of Figure 1 (note that \( C' \) may be a couple as above or one of success or fail) and we denote by \( \vdash_{SP} \) the reflexive and transitive closure of \( \vdash_{SP} \).

recu (for recurcall) is the main inference rule. It deals with the first filtering rule \( r_i \Rightarrow C \) of the FC given in the couple. The condition for the application of this rule is that the set of packets \( \text{dom}(r_i) \) filtered by this rule and not handled by the previous rules (i.e. not in \( D \)) would follow the same action \( C \) according to the security policy. Hence, successful repeated applications of recurcall ensures the soundness of the FC wrt the SP.

The success rule is applied under two conditions. First, recurcall must have been used successfully until all filtering rules have been processed (in this case the first component FC of the couple is empty). Second, the domain global security policy must be included in \( D \). This latter condition ensures that all the packets treated by the security policy are also handled by the firewall configuration (completeness of FC).

There are two cases for the application of failure. In the first case, failure is applied to a couple \( (FC, D) \) where FC is not empty. It means that recurcall has failed on this couple and hence that the FC is not sound wrt the SP. In this case, failure returns the first filtering rule of FC as a example of rule which is not correct, in order to provide help to the user in order to correct the FC. In the second case, failure is applied to \((\emptyset, D)\). It means that success has failed on this couple and that the FC is not complete wrt the SP. In this case, \( D \) is returned and can be used in order to identify packets handled by the SP and not by the FC.

\[\begin{align*}
\text{recu} & \quad \frac{(r \Rightarrow A); FC, D}{FC, D \cup \text{dom}(r)} \quad \text{if } \text{dom}(r) \setminus D \subseteq SP_A \\
\text{success} & \quad \frac{\emptyset, D}{success} \quad \text{if } D \supseteq \text{dom}(SP) \\
\text{failure} & \quad \frac{FC, D}{\text{fail}(fst(FC), D)} \quad \text{if no other rule applies}
\end{align*}\]

**Figure 1. Inference System**
Let us now prove that the inference system of Figure 1 is correct and complete. From now on, we assume given a FC 
\( FC = r_0 \Rightarrow A_0, \ldots, r_{n-1} \Rightarrow A_{n-1} \) with \( n > 0 \).

In the correctness theorem below, we assume that \( SP \) is consistent. We shall present in the next sections a method 
for checking this property.

**Theorem 1 (correctness)** Assume that the security policy \( SP \) is consistent. If \((FC, \emptyset) \vdash_{SP}^{*} success\) then the firewall configuration FC is sound and complete wrt SP.

**Proof.** If \((FC, \emptyset) \vdash_{SP}^{*} success\) then we have \((FC, \emptyset) \vdash_{SP} (FC_1, D_1) \vdash_{SP} \ldots \vdash_{SP} (FC_n, D_n)\) \vdash_{SP} success, where 
\( FC_n = \emptyset \), all the steps but the last one are recurrall and \( dom(SP) \subseteq D_n \). We can easily show by induction on that 
for all \( i \leq i \leq n \), \( D_i = \bigcup_{j<i} dom(r_j) \). Let \( D_0 = \emptyset \).

Assume that there exists \( p \in \mathcal{P} \) and \( r_i \Rightarrow A_i \) in FC 
(i < n) such that \( p \in dom(r_i) \setminus \bigcup_{j<i} dom(r_j) \). It follows that \( p \in dom(r_i) \setminus D_i \), and, by the condition of recurrall that \( p \in SPA_i \). Hence FC is sound wrt SP.

Let \( A \in \{\text{accept, deny}\} \) and \( p \in SPA \). By the condition of the inference rule success, \( p \in D_n = \bigcup_{j<i} dom(r_j) \). Let \( i \) be the smallest integer \( k \) such that \( p \in dom(r_k) \). It means that \( p \in dom(r_k) \setminus \bigcup_{j<i} dom(r_i) \). As above, it follows that \( p \in SPA_i \), and hence that \( A_i = A \), by the hypothesis that \( SP \) is consistent. Therefore, FC is complete wrt SP.

**Theorem 2 (completeness)** If the firewall configuration FC is sound and complete wrt the security policy SP then \((FC, \emptyset) \vdash_{SP}^{*} success\).

**Proof.** Assume that FC is sound and complete wrt SP. The soundness implies that for all \( i < n \) and all packet \( p \in dom(r_i) \setminus \bigcup_{j<i} dom(r_i), p \in SPA_i \). It follows that 
\( FC, \emptyset \vdash_{SP}^{*} (FC_1, D_1) \vdash_{SP} \ldots \vdash_{SP} (FC_n, D_n)\) with 
\( D_i = \bigcup_{j<i} dom(r_j) \) for all \( i \leq n \) and \( FC_n = \emptyset \), by application of the inference recurrall. Moreover, the completeness of FC implies that every \( p \in dom(SP) \) also belongs to \( D_n \). Hence \((FC, \emptyset, D_n) \vdash_{SP} success\), and altogether \((FC, \emptyset) \vdash_{SP}^{*} success\).

**Theorem 3 (soudness of failure)** If \((FC, \emptyset) \vdash_{SP}^{*} fail\) then the firewall configuration FC is not sound or not complete wrt the security policy SP.

**Proof.** Either we can apply iteratively the recurrall rule starting with \((FC, \emptyset)\), until we obtain \((\emptyset, \bigcup_{j<n} dom(r_j))\), or one application of the recurrall rule fails. In the latter case, there exists \( i < n \) such that 
\( dom(r_i) \setminus \bigcup_{j<i} dom(r_j) \not\subseteq SPA_i \). Therefore, there exists \( p \in P \) such that \( p \in dom(r_i) \setminus \bigcup_{j<i} dom(r_j) \) and \( p \not\in SPA_i \). It follows that FC is not sound wrt the security policy SP.

If \((FC, \emptyset) \vdash_{SP}^{*} P(\emptyset, \bigcup_{j<n} dom(r_j))\) using recurrall but the application of the success rule to the last couple fails, then there exists \( A \in \{\text{accept, deny}\} \) and \( p \in SPA \) such that \( p \not\in \bigcup_{j<n} dom(r_j) \). It follows that FC is not complete wrt the security policy SP.

Since the application of the inferences to \((SP, \emptyset)\) always terminates, and the outcome can only be success or fail, it follows immediately from the Theorem 1 that if the firewall configuration FC is not sound or not complete wrt the security policy SP, then \((FC, \emptyset) \vdash_{SP}^{*} fail\) (completeness of failure).

To summarize the above results, we have the following sufficient and necessary conditions for

**soundness:** \( \forall i < n, dom(r_i) \setminus \bigcup_{j<i} dom(r_j) \subseteq SPA_i \),

**completeness:** soundness and \( dom(SP) \subseteq \bigcup_{i<n} dom(r_i) \).

4 Verification Procedures

We describe in this section how to express the conditions for the above inference system of Section 3 as satisfiability problems for propositional formulae.

We consider a security policy which is presented as a finite set of directives: \( SP = \{c_i \Rightarrow A_i \mid 1 \leq i \leq m\} \). Each directive can be simple or complex. A simple directive describes whether a traffic destined to one or more services that are required by one or more sources and given by one or more destinations (as described by the condition \( c_i \)) must be accepted or refused (according to \( A_i \in \{\text{accept, deny}\} \)). A complex directive is basically a simple directive but considering some exceptions defined in \( e_i \). The following examples are respectively simple and complex directives.

- A sub network LAN\(_A\) has the right to access to the web service provided by a machine B located in the sub network LAN\(_B\).

- A sub network LAN\(_A\), except the machine \( A'\), has the right to access to the web service provided by a machine B located in the sub network LAN\(_B\).

The condition of the above second directive refers to the flow between the source LAN\(_A\) and the destination \( B\), the directive action is \( \text{accept}\), and its exception is the source machine \( A'\). The conditions and the exceptions are expressed as conjunctions of logic propositions describing

\[
\begin{align*}
  e_1 & \Rightarrow \text{accept} & e_1 \\
  e_2 & \Rightarrow \text{deny} \\
  e_3 & \Rightarrow \text{accept} \\
  e_4 & \Rightarrow \text{deny}
\end{align*}
\]

Figure 2. A Security Policy
the following main fields: source(s), destination(s) and service(s).

4.1 Security Policy Consistency

As explained in Section 3, the SP must be consistent in order to ensure the correctness of the verification method. Hence in a first step, we shall check that the domains of accepted and denied packets, $SP_{accept}$ and $SP_{deny}$, do not overlap. The set of accepted packets $SP_{accept}$, is the union of one set for each directive. Each set represents either the domain of a simple directive, if the action of the corresponding condition is accept, or the domain of a complex directive’s exception, if its action is deny or else the difference between the domains of the condition and the exception of a complex directive if its main action is accept. The set of denied packets is defined symmetrically. We express the above sets by propositional formulas $\phi_a$ and $\phi_d$ defining respectively the domains of accepted and denied packets. In the case of the SP of Figure 2, their definitions are

$$\phi_a := (c_1 \land \neg e_1) \lor c_1 \lor e_4$$

$$\phi_d := e_1 \lor e_2 \lor (e_4 \land \neg e_4)$$

In order to ensure that the domains do not overlap, we prove the insatisfiability of the following propositional formula $\phi_a \land \phi_d$. It ensures that no packet satisfies simultaneously $\phi_a$ and $\phi_d$.

4.2 Soundness Verification

Our goal is to check whether a firewall configuration $FC = \{r_i \Rightarrow A'_i | 0 \leq i < n\}$ is sound wrt the above security policy $SP$.

According to Section 3, the condition for the soundness of $FC$ wrt $SP$ is that, for each filtering rule $r_i \Rightarrow A'_i$, the domain $dom(r_i)$ minus the accumulated domains of the previous rules, is included in the set of packets that should undergo, according to $SP$, the same action as $A'_i$ of the filtering rule. The soundness condition is equivalent to the insatisfiability of all the following propositional formulae, for $0 \leq i < n$ (expressing the negation of the soundness condition in Section 3): $\phi_i \land \neg \phi_{A'_i}$, where $\phi_i := \phi_{r_i} \land \neg (\lor_{j=1}^{i-1} \phi_{r_j})$ and $\phi_{A'_i}$ is defined as above.

4.3 Completeness Verification

As explained in Section 3, in order to verify the completeness property of a firewall configuration, we check that the domain of the security policy $SP$ is included in that of the firewall configuration $FC$. These domains are made of the unions of the respective domains of filtering rules and security directives, as expressed by the following formulae:

$$\phi_{SP} := \bigvee_{i=1}^{m} c_i$$

$$\phi_{FC} := \bigvee_{i=0}^{n-1} r_i$$

The completeness condition of Section 3 is the insatisfiability of of the following formula: $\phi_{SP} \land \neg \phi_{FC}$.

5 Automatic Verification tool

The above presentation of the conditions of Section 3 permits the automation of the verification of soundness and completeness of FC wrt SP. In fact, in the previous section, these properties are expressed as satisfiability problems.

We have used a recent satisfiability solver modulo theories, Yices [5], in order to describe the different inputs and to automate the verification process. Yices provides different additional functions, compared to simple satisfiability solvers. These functions are based on theories like those of arrays, list structures and bit vectors.

The first input of our verification tool is a set of firewall rules. Each rule is defined by a priority order and composed of the following main fields: the source, the destination, the protocol and the port. The source and destination fields correspond to one or more machines identified by an IPv4 address and a mask coded both on 4 bytes, each bit being represented by a proposition variable. For better readability, we consider in this section the IP coding on 4 bits. For example, the following expression written in Yices syntax refers to the third filtering rule concerning UDP or TCP flow, coming from the source network 1.0.0.0/2 and reaching the network 1.1.0.0/3 for a destination port belonging to the subrange [20 – 60].

$$\text{(define r::int boole)} \text{ (assert (=} r 3 \text{ (and ips4 (not ip3) ipd4 ipd3 (not ipd2) (>= post 20) (<= post 60) (or (=} \text{protocol tcp} (=} \text{protocol udp)))))}}.$$  

In order to illustrate the verification procedure proposed, we have chosen to apply our method to a case study of a corporate network represented in Figure 3. The network is divided into three zones delineated by branches of a firewall whose initial configuration $FC$ corresponds to the rules in Table 1. The security policy $SP$ that should be respected contains the following directives.

$s_{p_1}$: $\text{net}_1$ has the right to access to $\text{net}_2$.

$s_{p_2}$: The machine $\text{admin}$ has the right to access to the FTP service provided by the FTP server belonging to $\text{net}_3$.

$s_{p_3}$: $\text{net}_1$ has not the right to access to the DNS service provided by the DNS server belonging to $\text{net}_2$.

In the following, we note that $d_i$ and $d'_i$ are respectively the condition and the exception of the security directive $s_{p_i}$.
Our goal is to verify that the configuration $FC$ is conform to the security policy $SP$ by checking the soundness and the completeness properties. But first, we must verify that the security policy is consistent.

5.1 Security Policy Consistency Verification

After we specified the security policy $SP$ in Yices syntax, checking the consistency of $SP$ amounts to check satisfiability. We have obtained the satisfiability result displayed in Figure 4.

Note that the Yices option e (evidence) displays a model if the logic expression is satisfiable. In our case, this means that the security policy is not consistent. An analysis of the model obtained shows that the directives $sp_1$ and $sp_3$ have contradictory decisions. It concerns on the flow coming from a machine belonging to net_1 and destined the DNS service of the DNS server 1.0.0.1. Indeed, the third directive indicates that the network net_1 has not the right to access to the DNS server of net_2 while the first directive permits it. One possible correction would be to replace the two directives in conflict by the following single complex directive.

Table 1. Firewall Configuration to be Verified

<table>
<thead>
<tr>
<th>$r_1$</th>
<th>$src_adr$</th>
<th>$dst_adr$</th>
<th>$protocol$</th>
<th>$dst_port$</th>
<th>$action$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_1$</td>
<td>1.1.1.1</td>
<td>0.1.1.1</td>
<td>21</td>
<td>tcp</td>
<td>accept</td>
</tr>
<tr>
<td>$r_2$</td>
<td>1.1.1.0</td>
<td>1.0.0.1</td>
<td>53</td>
<td>udp</td>
<td>deny</td>
</tr>
<tr>
<td>$r_3$</td>
<td>1.1.1.0/3</td>
<td>1.0.0.0/3</td>
<td>*</td>
<td>*</td>
<td>accept</td>
</tr>
</tbody>
</table>

5.2 Soundness Verification

Once ensured that the security policy is consistent, we proceed to the verification of the firewall configuration soundness, using the formulae of Section 4, which express the conditions of Section 3. The satisfiability result obtained is displayed in Figure 5. The outcome shows that the firewall configuration $FC$ is not sound wrt the security policy $SP$; i.e. that there exists some packets that will undergo an action different of that imposed by the security policy. It indicates also that $r_3$ is the first rule that causes this discrepancy precisely with the exception of directive $sp_1$. Indeed, the model returned corresponds to a packet accepted by the firewall through the rule $r_3$ while it should be refused according to the first directive of the security policy. This conflict can be resolved by adding a rule immediately preceding the rule $r_3$, which allows to implement the first directive exception precised by the given model. Table 2 presents this modification.

Table 2. A Sound Firewall Configuration

<table>
<thead>
<tr>
<th>$r_1$</th>
<th>$src_adr$</th>
<th>$dst_adr$</th>
<th>$protocol$</th>
<th>$dst_port$</th>
<th>$action$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_1$</td>
<td>1.1.1.1</td>
<td>0.1.1.1</td>
<td>21</td>
<td>tcp</td>
<td>accept</td>
</tr>
<tr>
<td>$r_2$</td>
<td>1.1.1.0</td>
<td>1.0.0.1</td>
<td>53</td>
<td>udp</td>
<td>deny</td>
</tr>
<tr>
<td>$r_3$</td>
<td>1.1.1.1</td>
<td>1.0.0.1</td>
<td>53</td>
<td>udp</td>
<td>deny</td>
</tr>
<tr>
<td>$r_4$</td>
<td>1.1.1.0/3</td>
<td>1.0.0.0/3</td>
<td>*</td>
<td>*</td>
<td>accept</td>
</tr>
</tbody>
</table>

5.3 Completeness Verification

After that the soundness property has been established, we proceed to the verification of the completeness of the firewall configuration. We obtained the satisfiability result displayed in Figure 6.

According to this outcome, the configuration $FC$ is not complete wrt the security policy $SP$: some packets handled by the security policy are not treated by the filtering rules. Indeed, the rule $r_4$ addresses only a subnetwork of net_2.

Figure 3. Network Architecture Example

Table 1. Firewall Configuration to be Verified

<table>
<thead>
<tr>
<th>$r_1$</th>
<th>$src_adr$</th>
<th>$dst_adr$</th>
<th>$protocol$</th>
<th>$dst_port$</th>
<th>$action$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r_1$</td>
<td>1.1.1.1</td>
<td>0.1.1.1</td>
<td>21</td>
<td>tcp</td>
<td>accept</td>
</tr>
<tr>
<td>$r_2$</td>
<td>1.1.1.0</td>
<td>1.0.0.1</td>
<td>53</td>
<td>udp</td>
<td>deny</td>
</tr>
<tr>
<td>$r_3$</td>
<td>1.1.1.0/3</td>
<td>1.0.0.0/3</td>
<td>*</td>
<td>*</td>
<td>accept</td>
</tr>
</tbody>
</table>

Figure 5. Soundness verification

sp_1: net_1 has the right to access to net_2 except the DNS server (DNS service).

Figure 4. Coherence verification

Figure 6. Completeness verification
The packet corresponding to the model returned belongs to another part of net_2, which is untreated. One possible solution would be to change, as shown in Table 3, the mask used in the destination address of the rule \( r_4 \) to consider all the first directive domain.

\[
\begin{array}{c|c|c|c|c}
\text{src adr} & \text{dst adr} & \text{protocol} & \text{dst port} & \text{action} \\
\hline
r_1 & 1.1.1.1 & 0.1.1.1 & \text{tcp} & \text{accept} \\
r_2 & 1.1.1.0 & 1.0.0.1 & \text{udp} & \text{deny} \\
r_3 & 1.1.1.1 & 1.0.0.1 & \text{udp} & \text{deny} \\
r_4 & 1.1.1.0/3 & 1.0.0.0/2 & * & * & \text{accept} \\
\end{array}
\]

Table 3. A sound and complete FC

We note that YICES validated the three properties after the modifications taken in sections 5.1, 5.6 and 5.3 by displaying in each case an insatisfiability result.

5.4 Experimental Results

In order to better assess the performance of the Yices tool for checking satisfiability of propositional formulas, we consider time treatment factor that we review by varying the different parameter sizes provided by the solver. In overall terms, we consider the average processing time of the three verification procedures (security policy consistency, firewall configuration soundness and completeness) by varying the total number of Boolean variables used. We note that we treat real field values such IPv4 address and [1-65535] port range. To perform this study, we used the option \texttt{stat} of Yices to collect statistical information. The experimental tests were conducted on an Intel Dual core 1.6 GHz with 1 Gbyte of RAM.

\[
\begin{array}{c|c}
\text{tool var nb} & \text{processing time(s)} \\
\hline
20 & 0.004 \\
65 & 0.020 \\
79 & 0.028 \\
155 & 0.09 \\
179 & 0.21 \\
\end{array}
\]

Table 4. Processing time evaluation

The experimental results are summarized in Table 4. The tool processing time obtained shows that our tool performed efficiently on the case studies.

6 Conclusion

In this paper, we propose a formal method for certifying automatically that a firewall configuration is sound and complete wrt a security policy. Otherwise, the method provides key information helping users to correct configuration errors. Our method permits also to prove the consistency of a security policy which is a necessary condition for the verification procedure. Finally, our method has been implemented using the satisfiability solver Yices. The experimental results obtained are very promising.

As further work, we are considering to extend the approach in order to handle stateful firewall configurations.

References