A HEURISTIC POLYNOMIAL ALGORITHM FOR LOCAL INCONSISTENCY DIAGNOSIS IN FIREWALL RULE SETS

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Abstract: Firewall ACLs can contain inconsistencies. There is an inconsistency if different actions can be taken on the same flow of traffic, depending on the ordering of the rules. Inconsistent rules should be notified to the system administrator in order to remove them. Minimal diagnosis and characterization of inconsistencies is a combinatorial problem. Although many algorithms have been proposed to solve this problem, all reviewed ones work with the full ACL with no approximate heuristics, giving minimal and complete results, but making the problem intractable for large, real-life ACLs. In this paper we take a different approach. First, we deeply analyze the inconsistency diagnosis in firewall ACLs problem, and propose to split the process in several parts that can be solved sequentially: inconsistency detection, inconsistent rules identification, and inconsistency characterization. We present polynomial heuristic algorithms for the first two parts of the problem: detection and identification (diagnosis) of inconsistent rules. The algorithms return several independent clusters of inconsistent rules that can be characterized against a fault taxonomy. These clusters contains all inconsistent rules of the ACL (algorithms are complete), but the algorithms not necessarily give the minimum number of clusters. The main advantage of the proposed heuristic diagnosis process is that optimal characterization can be now applied to several smaller problems (the result of the diagnosis process) rather than to the whole ACL, resulting in an effective computational complexity reduction at the cost of not having the minimal diagnosis. Experimental results with real ACLs are given.

1 INTRODUCTION

A firewall is a network element that controls the traversal of packets across different network segments. It is a mechanism to enforce an Access Control Policy, represented as an Access Control List (ACL). An ACL is in general a list of linearly ordered (total order) condition/action rules. The *condition* part of the rule is a set of condition attributes or selectors, where $|condition|=k$ (k is the number of selectors). The *condition* set is typically composed of five elements, which correspond to five fields of a packet header (Taylor, 2005). In firewalls, the process of matching TCP/IP packets against rules is called filtering. A rule matches a packet when the values of each field of the header of a packet are subsets or equal to the values of its corresponding rule selector. The *action* part of the rule represents the action that should be taken for a matching packet. In firewalls, two actions are possible: *allow* or *deny* a packet. A firewall ACL is commonly denominated a *rule set*.

Firewalls have to face many problems in real-life modern networks (Wool, 2004). One of the most important ones is rule set consistency. Selectors of rules can overlap (for example, the protocol selector), and can even be rules that are totally equal to others. Since a packet can be matched with any of the overlapping rules, firewalls usually use a positional conflict resolution technique, taking the action of the first matching rule. An inconsistent firewall ACL implies in general a design error, and indicates that the firewall is accepting traffic that should be denied or vice versa.

The minimal inconsistency characterization is a combinatorial problem. Although many algorithms have been proposed to solve it, to the best of our knowledge, all of them are brute force. These results return an optimal characterization, but make the problem intractable for large real-life rule sets.

In this paper we propose to take a different approach in order to make the problem tractable for real-life, big rule sets. We propose to divide consistency management in three sequential stages:

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- Inconsistency detection. It is the action of finding the rules that are inconsistent with other rules
- Identification of inconsistent rules. Finding the rules that cause the inconsistencies among the detected inconsistent rules, and whose removal produces a consistent rule set.
- Inconsistency characterization is understood as the action of naming the identified inconsistent rules among an established taxonomy of faults.

This paper focuses in the first two parts of the process (detection and identification, diagnosis). As we will show, detection is a problem that can be solved in polynomial time with complete algorithms. However, optimal identification and characterization are combinatorial problems. In this paper, we propose best case $O(n)$ and worst case $O(n^2)$ time complexity order independent detection and identification algorithms with the number of rules of the rule set, n. Algorithms are capable of handling full ranges in rule selectors without doing rule decorrelation, range to prefix conversion, or any other pre-process. A Java tool is available.

We consider this work a significant advance in consistency diagnosis in firewall rule sets because isolating diagnosis from characterization can reduce the effective computational complexity of optimal characterization algorithms, since they can now applied to several smaller problems (the result of the diagnosis stage) rather than to a big one (the full rule set). The work presented in this paper is an improvement over a previous presented one (Pozo, 2008). In this paper, best case has been improved by and order of magnitude and worst case by a constant. Although the worst case improvement may not seem representative in theoretical results, we will show that this improvement is very important in real-life rule sets, since they are near the best case.

This paper is structured as follows. In section 2, we analyze the internals of the consistency management problem in firewall rule sets. In section 3 we propose the consistency-based diagnosis algorithms, give a theoretical complexity analysis and experimental results with real rule sets. In section 4 we review related works comparing them to our proposal. Finally we give some concluding remarks in section 5.

2 ANALYSIS OF THE CONSISTENCY PROBLEM

To understand the problem, it is important to firstly review the inconsistencies characterized in the bibliography. A complete characterization that includes shadowing, generalization, correlation and redundancy has been given in (Al-Shaer, 2006). Although all of these are inconsistencies, usually not all are considered to be errors, as it can be used to cause desirable effects. All of these inconsistencies except redundancy are graphically represented in Fig. 1. For the sake of simplicity, only two rule inconsistencies with one selector are represented. An example of an ACL is presented in Table 1.

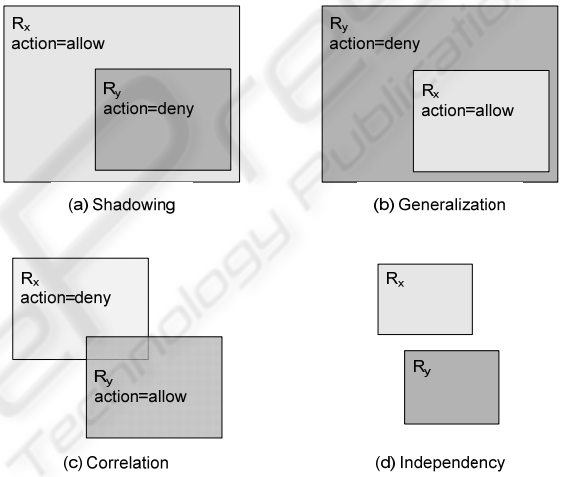

Figure 1: Graphical representation of three inconsistencies.

In this paper, we propose to divide consistency management in three sequential stages (Fig. 2). In the first step, all inconsistent rules are detected. Then, the minimal number of rules that cause the detected inconsistencies should be identified. Their removal guarantees that the resulting rule set is consistent. These two stages are called Inconsistency Diagnosis. Finally, the identified inconsistent rules are characterized among a established taxonomy of firewall rule set inconsistencies. The detection part of the process can be solved with complete polynomial algorithms (the most important are reviewed in the related works section, and a new one is proposed in this paper). The minimal identification is a combinatorial problem, as is going to be showed in the next section. A polynomial heuristic algorithm is proposed in this paper. The third and last problem is also combinatorial (Pozo4, 2008) (the most important works are reviewed later in this paper). Diagnosis is also rule-order

Table 1: Example of a Firewall Rule Set.

Priority/ID	Protocol	Source IP	Src Port	Destination IP	Dst Port	Action
R1	tcp	192.168.1.5	any	*.*.*.*	80	deny
R2	tcp	192.168.1.*	any	*.*.*.*	80	allow
R3	tcp	*.*.*.*	any	172.0.1.10	80	allow
R4	tcp	192.168.1.*	any	172.0.1.10	80	deny
R5	tcp	192.168.1.60	any	*.*.*.*	21	deny
R6	tcp	192.168.1.*	any	*.*.*.*	21	allow
R7	tcp	192.168.1.*	any	172.0.1.10	21	allow
R8	tcp	*.*.*.*	any	*.*.*.*	any	deny
R9	udp	192.168.1.*	any	172.0.1.10	53	allow
R10	udp	*.*.*.*	any	172.0.1.10	53	allow
R11	udp	192.168.2.*	any	172.0.2.*	any	allow
R12	udp	*.*.*.*	any	*.*.*.*	any	deny

independent, contrarily to characterization. The main difference of this work with other ones is that other authors apply brute force algorithms to solve directly the characterization problem, with no previous diagnosis. This yields algorithms that cannot be applied to big rule sets. With the proposed approach, the same characterization algorithms can be applied to several smaller problems, rather than to the full rule set. However, the number of these smaller problems is not minimal with the given heuristic algorithms proposed in this paper. In addition, heuristic characterization algorithms (Pozo4, 2008) can also be used to make the problem fully tractable.

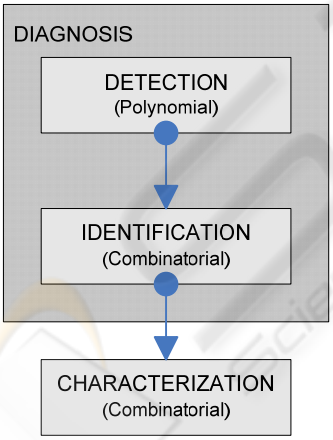

Figure 2: Consistency management process.

2.1 One to One Consistency in Firewall Rule Sets

First, it is needed to formalize a firewall rule set.

- Let *RS* be a firewall rule set consisting of *n* rules, $RS = \{R_1, ...R_n\}$.
- Let $R =< H, Action >, H \in \mathbb{N}^5$ be a rule, where $Action = \{allow, deny\}$ is its action.
- Let $R_j[k], 1 \le k \le n, k \in$
- $\{protocol, src\_ip, src\_prt, dst\_ip, dst\_prt\}$ be a selector of a firewall rule R_j.
- Let '<' and '>' be operators defined over the priority of the rules, where $R_x < R_y$ implies that then R_x has more priority than R_y and its action is going to be taken first, and vice versa.

Attending to Al-Shaer characterization, two rules (R_x, R_y) are correlated if they have a relation between all of its selectors, and have different actions. Fig. 1(c) represents a correlation inconsistency between two rules with one selector each. As the figure shows, the relation between the rules is not subset, nor superset, nor equal (rules R1 and R3 of Table 1 are correlated). Fig. 1(a) represents a shadowing inconsistency between two rules. The relation is equality or subset of the shadowed rule, R_y, respect to the general rule, R_x, with $R_x > R_y$ (R4 is shadowed by R3 in Table 1 example). Fig. 1(b) represents a generalization inconsistency between two rules, which is the inverse of shadowing respect to the priority of the rules. The relation is superset of the general rule respect to the other one (R2 is a generalization of R3 in Table 1 example).

Since we are only interested in diagnosis and not in characterization, let's try to remove names and give a general case of inconsistency based on these inconsistency characterizations (except redundancy). In a closer look at shadowing and generalization inconsistencies in Fig. 1, it can be seen that, in reality, these two inconsistencies are the same one, and the only thing that differentiates them is the priority of the rules. Thus, if priority is ignored, these two inconsistencies are special cases of a

correlation. That is, shadowing can be redefined as a correlation where all selectors of one rule (the shadowed one) are subsets or equal of the general rule. As generalization is the inverse with respect to the priority of shadowing, a generalization inconsistency can also be redefined as a correlation where of all selectors of a rule (the general one) are supersets of the other rule. So, the correlation inconsistency can be redefined as the superset of all inconsistencies, representing the most general case. For that reasons, it is possible to define *rule inconsistency* in only one priority independent case that recognizes all characterized inconsistencies. This is a key issue for our diagnosis process.

Definition 2.1. Inconsistency. Two rules $R_i, R_j \in RS$ are *inconsistent* if and only if the intersection of *each of all* of its selectors *R[k]* is not empty, and they have different actions, *independently of their priorities*. The inconsistency between two rules expresses the *possibility* of an undesirable effect in the *semantics* of the rule set. The semantics of the rule set changes if an inconsistent rule is removed.

$$Inconsistent(R_i, RS), 1 \le i \le n \Leftrightarrow \exists R_j \in RS, 1 \le j \le n, j \ne i \bullet$$

$$R_i[k] \cap R_j[k] \ne \varnothing \wedge R_i[Action] \ne R_j[Action]$$

$$\forall k \in \{protocol, src\_ip, src\_prt, dst\_ip, dst\_prt\}$$

Inconsistency of one rule in a RS

$$Inconsistent(R_i, R_j, RS), 1 \le i, j \le n, i \ne j \Leftrightarrow$$

$$R_i[k] \cap R_j[k] \ne \varnothing \wedge R_i[Action] \ne R_j[Action]$$

$$\forall k \in \{protocol, src\_ip, src\_prt, dst\_ip, dst\_prt\}$$

Inconsistency between two rules in a RS

This definition can be extended to more than two rules, as is going to be explained in the next section. Attending to Definition 2.1, all cases represented in Fig. 1 are of the same kind, and are called *inconsistencies* without any particular characterization. Priority is only required if inconsistencies are going to be characterized. We showed that all inconsistencies between pairs of rules can be detected by pairs of two with Definition 2.1, but more complicated situations must also be analyzed in order to illustrate this definition. In next sections we show that no extension is needed to Definition 2.1, since the case of *n to one* rule inconsistency can be decomposed in several independent two-rule inconsistencies.

2.2 One to Many Consistency in Firewall Rule Sets

All base situations are presented in Fig. 3, which is an extension to Fig. 1. This figure is a simplification to three inconsistent rules, but can easily be extended to more rules that can be composed in several ways.

Fig. 3(a1) represents an inconsistency where the union of two independent rules R_x, R_y overlaps with another one, R_z (Fig. 4(a) taken from (García-Alfaro, 2007) exemplifies this situation). As R_x is inconsistent with R_z, and R_y is also inconsistent with R_z, both in an independent manner, this situation can be decomposed in two independent inconsistencies, and can easily be diagnosed.

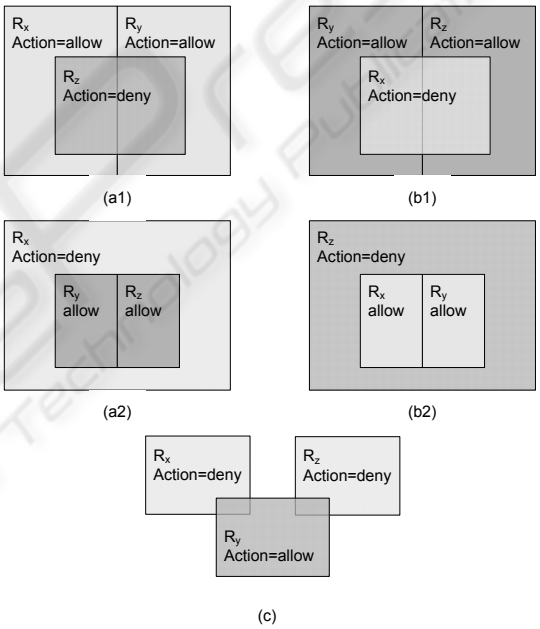

Figure 3: Graphical representation of inconsistencias between three rules.

Fig. 3(a2) presents a similar situation, where R_x overlaps with the union of R_y and R_z. This situation is also decomposable in two independent inconsistencies: R_x inconsistent with R_y, and R_x with R_z. Note that, in order to diagnose inconsistencies, the priority of the rules is not necessary.

The situations presented in Fig. 3(b1) and Fig. 3(b2) are the inverse of the two previous ones respect to the action. Thus, the diagnosis is analogous. This situation is exemplified in Fig. 4(b). Finally, Fig. 3(c) represents a relation with three overlapping rules (an example is in Fig. 4(c)). This situation can also be decomposed in two

independent ones: R_x inconsistent with R_y, and R_y with R_z.

In conclusion, it is possible to diagnose inconsistencies between an arbitrary number of rules with Definition 2.1, because all the presented situations can be decomposed in independent two by two relations. These examples are easily extendable to more than three rules.

$$Rx : \{port \in [10-50]\} \Rightarrow \{allow\}$$
$$Ry : \{port \in [40-90]\} \Rightarrow \{allow\}$$
$$Rz : \{port \in [30-80]\} \Rightarrow \{deny\}$$
(a)
$$Ry : \{port \in [10-50]\} \Rightarrow \{allow\}$$
$$Rz : \{port \in [40-90]\} \Rightarrow \{allow\}$$
$$Rx : \{port \in [0-100]\} \Rightarrow \{deny\}$$
(b)
$$Rx : \{port \in [0-50]\} \Rightarrow \{deny\}$$
$$Rz : \{port \in [60-100]\} \Rightarrow \{deny\}$$
$$Ry : \{port \in [40-70]\} \Rightarrow \{allow\}$$
(c)

Figure 4: Inconsistency examples.

If a new rule, R_z, is added to an *inconsistent* rule set, the new rule can only cause a new inconsistency with one to all of the rules in the rule set, in a similar way that it did in the previous case (Fig. 5). It cannot modify a previous inconsistency, or cause an inconsistency between two consistent rules, and without the new rule. This inconsistency can also be decomposed in two by two inconsistencies, which are independent of the inconsistencies that were present in the rule set previously to the addition of R_z. In the same way, if a new rule is inserted in a *consistent* rule set, a similar decomposition can be done (Fig. 6).

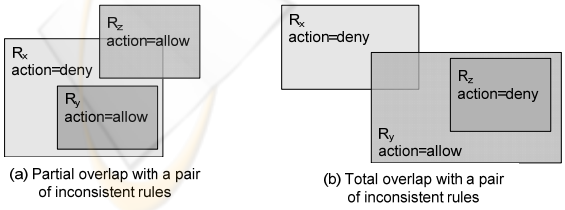

Figure 5: Graphical representation of a new inconsistent rule added in an inconsistent rule set.

Note that, as the diagnosis process is order-independent, the new rule can be inserted anywhere in the rule set. Again, these two situations can be easily extended to more than three rules.

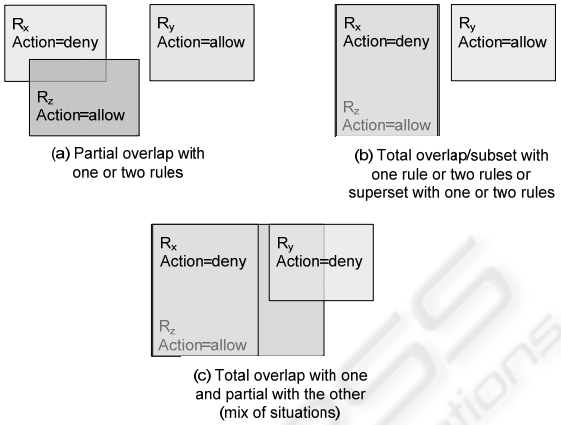

Figure 6: Graphical representation of a new inconsistent rule added in an consistent rule set.

3 CONSISTENCY-BASED DIAGNOSIS OF RULE SETS

The presented analysis has motivated the separation of characterization from diagnosis, and to solve the diagnosis problem in isolation, as a first stage for the optimal inconsistency characterization problem. As it is going to be showed, the result of the diagnosis process is the identification of the rules that cause the inconsistencies in the rule set and for each one, the set of the rules which they are inconsistent with. Each of these sets and their corresponding identified conflicting rule can be taken as input to the characterization part of the process, resulting in an effective computational complexity reduction (solving several small combinatorial problems is faster than solving a big one). However, recall that as the optimal identification of inconsistent rules is a combinatorial problem, the application of an optimal characterization algorithm to the result of the proposed heuristic diagnosis process is senseless. In contrast, heuristic characterization algorithms (Pozo4, 2008) can be used, with a heavy improvement in computational complexity of the full process.

In this section, two algorithms which implement Definition 2.1 and the diagnosis process explained in the previous section are presented. Algorithms are capable of handling ranges in all selectors.

3.1 Stage 1. Detection of Inconsistent Pairs of Rules

The first stage of the process detects the inconsistent rules of the rule set and returns an Inconsistency Graph (IG, Definition 3.1) representing their relations. Note that the detection process, like Definition 2.1, is order independent. Also note that the presented algorithm is complete, as it implements Definition 2.1 (which is complete).

Definition 3.1. Inconsistency Graph, IG. An IG is an undirected, cyclic and disconnected graph whose vertices are the inconsistent rules of the rule set, and whose edges are the inconsistency relations between the these rules. Note that |IG| is the number of inconsistent rules in *RS*, and ||IG|| corresponds with the number of inconsistencies pairs of rules in *RS,* or simple the number of inconsistencies in *RS*.

$$\text{Let } IG =< V, E > \text{ be an undirected, cyclic and disconnected graph}$$
$$V(IG) = R_i \in RS, 1 \le i \le n \bullet Inconsistent(R_i, RS)$$
$$E(IG) = R_i, R_j \in V, 1 \le i, j \le n, i \ne j \bullet Inconsistent(R_i, R_j, RS)$$

Algorithm 1 presented in Figure 7 (implemented in Object Oriented paradigm and using abstract data types) exploits the order independence of the inconsistency definition and only checks inconsistencies between rules with different actions, dividing the ACL in two lists, one with *allow* rules and the other with *deny* ones. The algorithm receives two rule sets. One of them is composed of *allow* rules and the other of *deny* rules of the original rule set. This decomposition is a linear complexity operation. The algorithm takes one of the rule sets and, for each rule, it checks if there is an inconsistency with other rules in the other one. As all inconsistencies can be decomposed in two by two relations, there is no need to check combinations of more than two rules. Each time the algorithm finds an inconsistency between a pair of rules, the two rules are added as vertices to the IG, with a non directed edge between them. The algorithm returns an IG. Since all possibilities have been checked, Algorithm 1 detects of all possible inconsistent rules (i.e. it is complete). Fig. 8 presents the resulting IG of the Table 1 example.

Time complexity of Algorithm 1 is bounded by the two nested loops (lines 8 and 10). Each rule in *ruleSetAllow* is tested for inconsistency against rules in *ruleSetDeny*. The worst case for the loop is reached when *ruleSetAllow.size()= ruleSetDeny.size()* (i.e. half rules *allow* and the other half *deny*), and the best case when *ruleSetAllow.size()=n* and *ruleSetDeny.size()=0* or *ruleSetAllow.size()=0* and *ruleSetDeny.size()=n*. Thus, the complexity of the improved detection algorithm depends on the percentage of *allow* and *deny* rules over the total number of rules.

Algorithm 1. Inconsistency Detection algorithm

```
1.      Func detection(in List: ruleSetAllow,
2.  ruleSetDeny; out Graph: ig)
3.      Var
4.        Rule ri, rj
5.        Integer i, j
6.      Alg
7.        for each j=1..ruleSetAllow.size() {
8.          rj= ruleSetAllow.get(j)
9.          for each i=1..ruleSetDeny.size() {
10.           ri = ruleSetDeny.get(i)
11.           if (inconsistency(ri, rj)) {
12.             ig.addVertex(ri)
13.             ig.addVertex(rj)
14.             ig.addEdge(ri, rj)
15.         }
16.       }
17.     }
18.   End Alg
19.
20.   // Implements the Inconsistency Definition
21.   Func inconsistency(in Rule: rx, ry; out
22. Boolean: b)
23.   Var
24.     Integer i
25.   Alg
26.     b = true
27.     i = 1
28.     while (i<=rx.selectors.size() AND b)
29.       b = b AND intersection(rx.getSelector(i),
30.                              ry.getSelector(i))
31.       i=i+1
32.     }
33. End Alg
```

Figure 7: Inconsistency detection algorithm.

However, there are other inner operations that should be analyzed in lines 12 to 15. The first one, in line 12, is *inconsistency()* which is composed of an iteration. This operation implements the inconsistency definition. In typical firewall ACLs, *k=5*, and thus the iteration runs 5 times. Anyway, the iteration is bounded by the number of selectors, which is a constant, *k.*

In addition, inside the iteration there is an intersection between each selector (lines 28 to 30). The typical 5 selectors of firewall ACLs (Table 1) are integers or ranges of them, except IP address.

Knowing if two ranges of integers intersect can be done in constant time with a naïve algorithm which compares the limits of the intervals. Knowing if two IP addresses intersect can also be easily done in constant time by comparing their network addresses and netmasks. Other operations of the inner loop (lines 12 to 14) are the graph-related ones. If the graph is based on hash tables, vertex and edge insertions run in constant time, except in some cases where rehashing could be necessary.

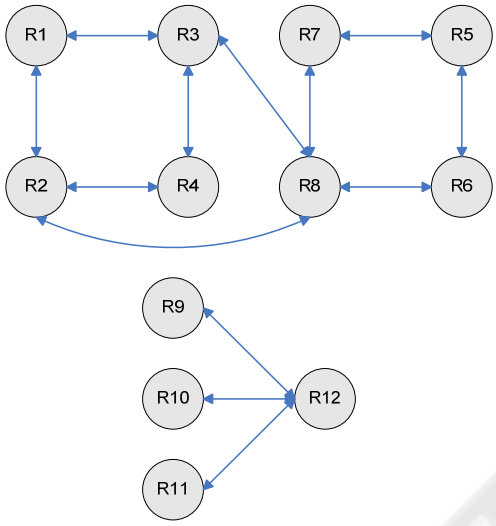

Figure 8: Inconsistency graph.

For all these reasons, the complexity of the two nested loops is only affected by a constant factor in all cases, which depends on the constant number of selectors, *k*. Thus, worst case time complexity of the detection algorithm is in $O(n^2)$, best case is in $O(n)$, and average case is in $O(n \cdot m)$ with the number of *allow* rules, *n*, and *deny* rules, *m* in the ACL.

Space used by Algorithm 1 is the sum of the space needed to store the ACL, and the one needed for the graph. In best case the graph would have *n* vertices and *n-1* edges. In the worst case, there could be *n-1* inconsistent rules and also *n-1* edges per vertex. Note that the space needed to store an edge is fewer than the needed to store a vertex, since only a reference between vertices is needed.

3.2 Stage 2. Detection of Inconsistent Pairs of Rules

The second and last stage of the diagnosis process identifies the rules that cause the inconsistencies from the set of inconsistent pairs of rules (the result of the previous stage) with an heuristic algorithm. Algorithm 2 (Fig. 9) was initially presented in (Pozo, 2008). It receives the IG as input and takes iteratively the vertex with the greatest number of adjacencies (lines 6 and 7), that is, the vertex with the greatest number of inconsistencies, *v*. Then, an independent cluster of inconsistent rules (ICIR, Definition 3.2) is created as a tree with *v* (the conflicting rule of the cluster) as its root, and its adjacents (the inconsistent rules) as leafs (lines 8 to 12). The root of all ICIRs from the Diagnosis Set (DS, Definition 3.3), or the set of rules that must be removed to get a consistent rule set. Then, *v* and its edges are removed from the IG (line 13). If vertices with no edges are left in the IG, then these vertices are removed (line 14), since they are consistent by definition (they are rules with no relations with others). As inconsistencies have been decomposed in pair wise relations, ICIRs are always formed by two levels. For the analyzed example, the algorithm finishes with a diagnosis set of cardinality five *(|DS|=5)*, containing the rules *DS={R8, R12, R5, R1, R4}*, which are the ICIR roots or the rules that cause an inconsistency with other ones. If all rules of *DS* are removed, the resulting rule set is consistent. R8 and R12 were the most conflicting ones . A trace of the different iterations of Algorithm 1 when applied to Table 1 was presented in (Pozo, 2008).

Algorithm 2. Inconsistent Rule Identification algorithm

```
1.      Func identification(in Graph:ig; out List of
2.  Tree:icirs)
3.      Var
4.          Tree icir
5.      Alg
6.          while (ig.hasVertices()) {
7.              Vertex v = ig.getMaxAdjacencyVertex();
8.              List adj = ig.getAdjacents(v)
9.              icir.createEmptyTree()
10.             icir.setRoot(v)
11.             icir.addChildren(adj)
12.             icirs.add(icir)
13.             ig.removeVertexWithEdges(v)
14.             ig.removeNotConnectedVertices()
15.         }
16. End Alg
```

Figure 9: Inconsistency identification algorithm.

Definition 3.2. Independent Cluster of Inconsistent Rules, ICIR. An *ICIR(root, CV)* is a two level tree, rooted in the rule *root* and where *CV* is a set of rules (its leafs). It represents a cluster of mutually consistent rules, *CV,* which are at the same time inconsistent with their *root. ICIR(root)* is the rule which has the greatest number of inconsistencies with other rules of the same cluster.

Note that the action *ICIR(root)* is the contrary of the actions of all of its leafs in *CV*.

$$ICIR(root, CV) \Leftrightarrow$$
$$\forall R_i \in CV \bullet Inconsistent(root, R_i) \wedge$$
$$\forall R_i, R_j \in CV, i \neq j \bullet \neg Inconsistent(R_i, R_j)$$

Definition 3.3. Diagnosis Set, DS. This is the set of rules that cause the inconsistencies, and coincide with the root of all ICIRs.

$$\text{Let } ICIRS = \{ICIR_1, ..., ICIR_m\}$$

be the set of all ICIR of a given *RS*, then

$$DS = \{ICIR_1(root), ..., ICIR_m(root)\}$$

If the rules from the DS are directly removed from the rule set, it gets consistent. Note that this heuristic is not necessarily minimal.

Time complexity of Algorithm 2 is bounded by the loop of line 5, which runs as many times as ICIRs are formed (it corresponds with the cardinality of the Diagnosis Set, *|DS|*). The worst case is reached, as in Algorithm 1, when *ruleSetAllow.size()=ruleSetDeny.size()=n/2* (Fig. 11(b)), resulting in a *|DS|=n/2*. In this case, *getMaxAdjacencyVertex()* (line 7), a maximum calculus, runs in *O(n)* with the number of vertices of the graph (the number of inconsistencies). Operations of lines 8, 9, 10, 11, and 12 run in constant time. *removeVertexWithEdges()* (line 13) runs in linear time with the cardinality of its adjacency list (*n/2-1* in the worst case). Finally, *removeUnconnectedVertices()* (line 14) is also linear with the number of vertices in the graph at each iteration, *O(n)*. Thus, the resulting worst case time complexity of Algorithm 2 is in $O(|DS| \cdot (n+n/2-1+n)) = O(n/2 \cdot n) = O(n^2)$.

The best case is reached, as in Algorithm 1, when *ruleSetAllow.size()=n* and *ruleSetDeny.size()=0* or vice versa (Fig. 11(a)). The IG only has one vertex, *v*, connected to all the other vertices. In this case, *|DS|=1* and the algorithm is in *O(n)*. In an average case the algorithm is in $O(|DS| \cdot h)$, $|DS| << h$ (*h* is the number of inconsistencies).

Algorithm 2 needs some space to store the ICIRs. Each ICIR needs space for its root and for the conflictive rules. But note that, as the algorithm is creating the ICIRs, the corresponding vertices and edges are removed from the IG, and thus at each iteration only the space to store the adjacency list of the removed vertex is necessary. Complexities are presented in Table 2.

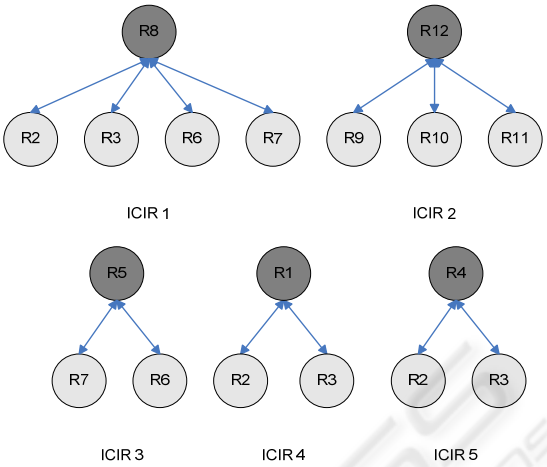

Figure 10: Generated ICIRs and the Diagnosis Set.

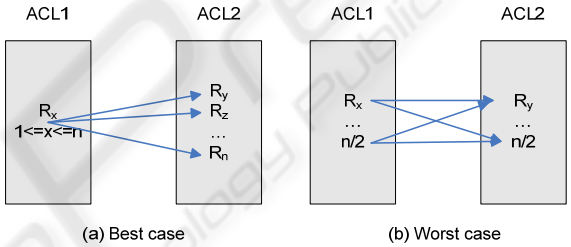

Figure 11: Identification best and worst cases.

The result of the diagnosis process is the set of all ICIRs. As each ICIR represent a different independent inconsistency, exhaustive search optimal characterization algorithms can be applied to each one independently, reducing the effective computational complexity of the whole process. In addition, heuristic characterization algorithms can also be applied (Pozo4, 2008) Also note that the presented proposal makes no assumptions about how selector ranges are expressed. This is important, because if the original rule set is directly used by algorithms, inconsistency results are given over the original, unmodified rule set.

Table 2: Detection and Identification Time Complexities.

Number of inserted rules	Best case	Average case	Worst case	Space Worst
Detection	*O(n)*	*O(n·m)*	$O(n^2)$	*n Rules·h Edges*
Identification	*O(n)*	$O(\|DS\| \cdot h)$, $\|DS\| << h$	$O(n^2)$	*n Rules·h Edges*
Combined (Diagnosis)	*O(n)*	*O(n·m)*	$O(n^2)$	*n Rules·h Edges*

Table 3: Performance Evaluation.

Size	%Deny	|DS|	Average ICIR size	#Inconsistencies	Detection (ms)	Identification (ms)	TOTAL (ms)
50	28,21	0	n/a	0	0,06	0	0,06
144	30,91	3	16	48	0,59	0,21	0,8
238	66,43	15	19	291	2,08	0,15	2,23
450	34,73	15	20	312	5,59	0,16	5,75
900	14,8	29	34	1005	13,38	0,64	14,02
2500	6,97	100	43	4337	59,48	4,08	63,56
5000	1,98	32	19	1388	63,93	1,18	65,11
10611	2,05	156	59	18894	346,58	24,79	371,37

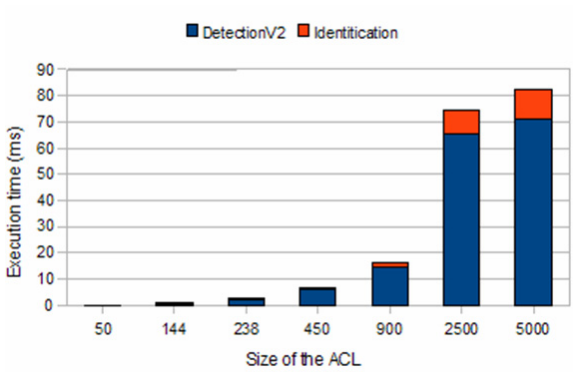

Figure 12(a): Running time. Average case

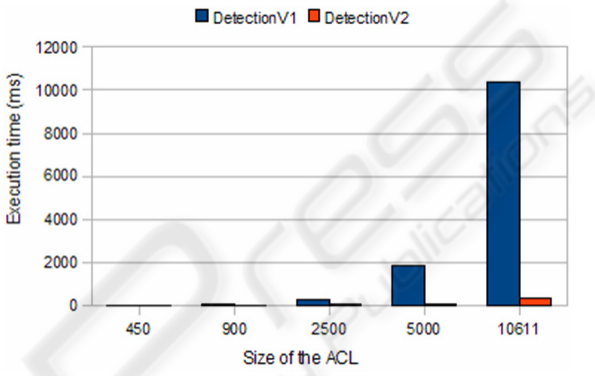

Figure 12(b): Comparison between detection algorithms.

3.3 Experimental Results

In absence of standard rule sets for testing, the proposed heuristic process has been tested with real firewall rule sets (Table 3). The first column represents the size of the rule set; the second one the percentage of deny rules over the rule set size; the third the cardinality of the Diagnosis Set, |DS|, (or the number of generated ICIRs), or the combinatorial problems to be solved by an optimal characterization algorithm; the fourth represents the average size of each ICIR (that is, the number of ICIRs divided by |DS|), or the average size of the characterization problems to be solved (how many rules are in them); the fifth the number of inconsistencies; and the sixth, seventh and last columns the execution time of the detection, identification and the sum of them.

The conducted performance analysis represents a wide spectrum of cases, with ACLs of sizes ranging from 50 to 10600 rules, and percentages of *allow* and *deny* rules ranging from 2% to 65%. Recall that worst case for the improved detection algorithm is half rules *allow* and the other half *deny*. Also note that real ACLs have some important differences with synthetically generated ones. The most important one is the number of *deny* and *allow* rules: as real firewall ACLs are usually designed with *deny all* default policy, most rules are going to have *allow* actions. In ACLs designed with *allow all* policy, most rules would have *deny* actions. Also note that, as the percentage of *allow* or *deny* rules decrease, the number of inconsistencies does necessarily not, because the number of inconsistencies depend on how many rules with different actions intersect. The result is that the worst case would not normally happen in real firewall ACLs. Experiments were performed on a Java implementation with Sun JDK 1.6.0_03 64-Bit Server VM, on an isolated HP Proliant 145G2 (AMD Opteron 275 2.2GHz, 2Gb RAM DDR400). Execution times are in ms. Tests have been run without wildcard rules (RW, *deny all* or *allow all* rules) because WR provide no useful information to the diagnosis process: they are conflictive by definition with all rules with the contrary action.

The experimental comparison of the efficiency of the proposed algorithms with others of the reviewed in the bibliography is a very difficult task for two main reasons. In one hand, there are no standard rule sets to be used. In other hand different algorithms cover different parts of the process. One of the most important parts of the presented experimental analysis is the average reduction of the full problem, and the size of each reduced part. Recall that optimal characterization algorithms can be applied now to each of these problems and solve them faster than running the characterization over the full rule set.

Unfortunately, there are neither standardized rule sets nor syntactic generation tools that can be used to test how near is the proposed heuristic to the optimum.

As Table 3 and Fig. 12(a) show, execution time for the diagnosis process is very reasonable, even in large rule sets. Note that rule set of sizes 238 and 450 are very near worst case. Rule set of size 10611 has not been represented to prevent image scale distortion, but note that even with a very high number of inconsistencies (18894) execution time of the full process is 371ms. Take into account that a rule set of 10611 rules is a very big one (Taylor, 2005). Fig. 12(b) presents a comparison between the previous detection algorithm (Pozo, 2008) and the one presented in this paper. Note how the previous version (DetectionV1) (Pozo, 2008) scale quadratically with the number of rules. However, the complexity of the new algorithm (DetectionV2) depends on the percentage of *allow* and *deny* rules. As can be seen, there is a huge difference with real rule sets.

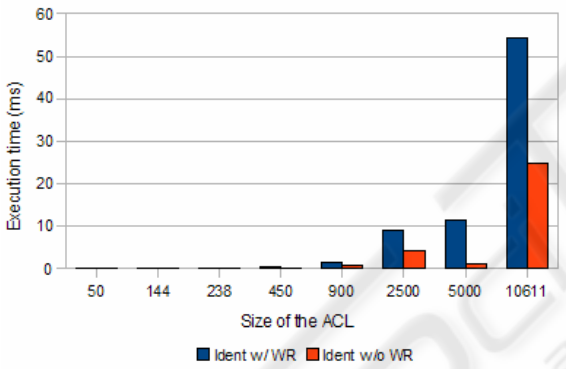

Figure 13: Identification with and without wildcard rules.

Fig. 13 represents a comparison of running times of the identification algorithm with and without wildcard rules, in order to highlight the impact these rules have in processing time. As we previously noted, leaving trailing wildcard rules for diagnosis purposes gives no useful information to the process, since they are conflictive with all rules with contrary action.

Other important things worth noting are the related with problem reduction. The average ICIR size in Table 3 (fourth column) represents the average number of children of each generated ICIR (the number of ICIRs is represented in the third column as the size of the Diagnosis Set, |DS|). That is, |DS| is the number of characterization problems to be optimally solved if optimal characterization algorithms are going to be used, and Average ICIR Size is their average size. Clearly, solving (optimally or not) such small number of small problems is faster than solving a big combinatorial one.

Finally, due to its low computational complexity, the presented detection algorithm can be used with very big rule sets or even in resource constrained devices (Pozo2, 2008) in a real time process.

4 RELATED WORKS

The closest works to ours are related with consistency detection in general network filters. In the most recent work, Baboescu et al. (Baboescu, 2003) provide algorithms to detect inconsistencies in router filters that are 40 times faster than $O(n^2)$ ones for the general case of k selectors per rule. Although its algorithmic complexity is not given, it improves other previous works (Hari, 2000), (Eppstein, 2001). However, they preprocess the rule set and convert selector ranges to prefixes, and then apply the algorithms. This imposes the implicit assumption that a range can only express a single interval, which is true (pozo3, 2008). However, the range to prefix conversion technique could need to split a range in several prefixes (Srinivasan, 1998) and thus the final number of rules could increase over the original rule set. Thus, results are given over the preprocessed rule set, which could be bigger and different from the original one.

Other researchers apply brute force, combinatorial algorithms for the characterization problem. Thus, the resulting worst case time complexity will be exponential in all these proposed algorithms. One of the most important advances was made by Al-Shaer et al. (Al-Shaer, 2004), where authors define an inconsistency model for firewall ACLs with 5 selectors. They give a combined algorithm to diagnose and characterize the inconsistencies between pairs of rules. In addition, they use rule decorrelation techniques (Luis, 2002) as a pre-process in order to decompose the ACL in a new, bigger, one with non overlapping rules. Results are given over the decorrelated ACL, which has the disadvantages commented above. Although the proposed characterization algorithm proposed by Al-Shaer is polynomial, a decorrelation pre-process imposes a worst case exponential time and space complexity for the full process.

A modification to their algorithms was provided by García-Alfaro et al. (García-Alfaro, 2007), where they integrate the decorrelation and characterization algorithms of Al-Shaer, and generate a decorrelated and consistent rule set. Thus, due to the use of the

same decorrelation techniques, this proposal also has worst case exponential complexity. The resulting ACL is also bigger and different from the original one. However, García-Alfaro et al. provide a characterization technique with multiple rules.

A similar approach to García-Alfaro was followed in (Abedin, 2006), where authors provide worst case $O(2^n)$ time complexity algorithms with the number of rules (they also use rule decorrelation techniques).

Ordered Binary Decision Diagrams (OBDDs) have been used in Fireman (Yuan, 2006), where authors provide a diagnosis and characterization technique with multiple rules. A very important improvement over previous proposals is that they do not need to decorrelate the ACL, and thus, results are given over the original one. Note that the complexity of OBDD algorithms depends on the optimal ordering of its nodes, which is a NP-Complete problem (Bollig, 1996). This results in a worst case $O(2^n)$ time complexity with the number of rules, as other proposals.

There are several differences of our work with these ones. In one hand, we provided an analysis of the consistency diagnosis problem in rule sets, separating diagnosis (detection and identification) from characterization, which enabled us to design heuristic polynomial diagnosis algorithms. The result of the diagnosis process is several independent clusters of inconsistencies, where optimal characterization algorithms can be applied, effectively reducing the computational complexity (in time and space) of the whole process. In addition, heuristic characterization algorithms can also be applied. This heuristic process provides an alternative to the reviewed brute force algorithms for big rule sets. However, characterization algorithms are not the focus of the paper, but the presentation of a novel process and diagnosis algorithms for the diagnosis part of the process. Our diagnosis algorithms have a theoretical best case $O(n)$ and worst case $O(n^2)$ time complexity with the number of rules in the rule set, n. More precisely, the complexity of our algorithms depends on the percentage of *allow* and *deny* rules over the total number of them (in the case of detection), and on the cardinality of the minimal diagnosis set and the number of inconsistencies (in the case of identification). Our process is capable of handling full ranges in all selectors, and does not need to decorrelate or do any range to prefix conversion to the ACL as a pre process to the algorithms. We think that for a result to be useful for a user, it should be given over the original ACL. However, our proposal does not cope with redundancies, because we redundancies are not a consistency problem.

5 CONCLUSIONS

We have deeply analyzed the consistency diagnosis problem in firewall ACLs, and decided to divide the consistency management process in three sequential stages: detection, identification, and characterization. Inconsistency detection is a polynomial problem, but minimal identification and characterization are combinatorial ones. Detection plus identification is called diagnosis. All reviewed proposals deal with the full characterization problem with brute force algorithms, with yield unusable results for real-life, big rule sets.

In this paper we take a different approach, isolating the combinatorial parts of the full problem (optimal identification and characterization) from the polynomial one (detection). We have proposed an abstract definition of inconsistency that covers all previously characterized cases in the bibliography. Based on this definition, we revisited the consistency problem in firewall rule sets and showed that all relations between more than two rules can be decomposed in simpler pair wise relations.

We have proposed two polynomial algorithms that should be applied sequentially to get a diagnosis of the inconsistent rules in the rule set. The first one detects the inconsistent rules and is complete. The second one identifies the rules that cause the detected inconsistencies, and is based in a heuristic. The diagnosis can then be taken as input to optimal characterization algorithms resulting in an effective computational complexity reduction (solving several small combinatorial problems is faster than solving one big one), or to heuristic ones.

A theoretical complexity analysis has been done and showed that the full process has best case $O(n)$ and worst case $O(n^2)$ time complexity with the number of rules in the rule set, n. An experimental performance evaluation with real rule sets of different sizes was also presented, showing that real rule sets are very near to the best case, and the effective problem reduction. Unfortunately, there are neither standardized rule sets nor syntactic generation tools that can be used to test how near is the proposed heuristic to the optimum. We compared our proposal with other works in the bibliography and showed that, to the best of our knowledge, no proposals that split the consistency management process have been made. Thus, our work represents a completely different way to treat

the problem with algorithms that are useable with real-life, big rule sets. We have implemented the algorithms in Java language in a tool which is available under request.

However, our approach has some limitations that give us opportunities for improvement in future works. The most important one is that our process can diagnose inconsistent rules, but cannot diagnose redundant rules.

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