

An Optimized Firewall Anomaly Resolution

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ABSTRACT Firewalls are the key mechanism in cybersecurity, that has been widely used to ensure network security. In literature, several works have been proposed in the area of firewall rules managing, however, the correct firewall configuration still remains a complex and error-prone task. Anomalies among firewall rules can cause severe network breaches, such as allowing harmful packets to slip into a subnetwork or dropping legitimate traffic which in turn could hinder the correct availability of web services. This paper aims to help the network security administrators by introducing a formal approach that reduces the number of anomalies in firewalls' configurations that the administrators are usually obligated to manually solve. Moreover, the feasibility of the presented approach has been confirmed through a set of tests with a synthetic network.

INDEX TERMS Policy Based Systems Firewall, Policy Anomaly Management, Network Security

I. INTRODUCTION

FIREWALLS are known as a main architectural element for the security of every IT system. The last Verizon report clearly shows [1] that about 70% of cyber attacks discovered in 2019 had network/cloud services and resources as main targets. Firewalls have been widely used as the very first frontier to protect not only small individual and local networks, but also large networks from these cyberattacks.

Moreover, nowadays firewalls are not used as perimetral defences only but are more and more adopted to protect internal layers in large networks, for instance in industrial networks and critical infrastructures, where defence in depth is required.

Unfortunately, the configuration of firewalls is mostly designed manually by network administrators, and the support of automatic or semi-automatic tools for this task, is limited. Of course, in this scenario, the possibility of introducing human errors in such configurations is high and this can have a great impact on the effectiveness of the firewall in providing an adequate security and protection level. This is even more critical in large networks and virtualized environments. Specifically, in large networks many security mechanisms are in place and flaws in a firewall configuration could easily propagate through the entire network. While in virtualized networks, the paths that traffic flows must cross can be defined at run-time by means of software programs (i.e., Soft-

ware Defined Network) [2], and the network functions can be virtualized so as to be deployed at on-demand on general-purpose servers (i.e., Network Functions Virtualization) [3].

In literature, several works have been proposed to automatically detect anomalies in a firewall configuration [4]–[14]. Moreover, some of the proposed works are also able to partially fix the detected anomalies, notwithstanding, automatic conflict resolutions are potentially very dangerous because they actually hide mistakes and conflicting requirements that, on the contrary, should be explicitly addressed by security administrators. For these reasons network security administrators prefer to manually solve firewall anomalies. However, the number of anomalies in firewalls are huge, since a firewall policy may consist of hundreds of rules, which are typically logically correlated with each other.

This paper aims to define a formal approach to select a minimum set of anomalies that, if solved, will result in the complete resolution of all the initially identified anomalies among the firewall rules.

The reduction of anomalies to solve, significantly simplifies and makes more effective the security administrator work, improving the overall quality and efficiency of the firewall configuration and thus increasing the global security of the network.

Specifically, we propose a model suitable to identify the relations among the fields of the firewall rules and among the

	priority	IPsrc	Psrc	IPdst	Pdst	Proto	Action
r_1	1	130.162.0.1	*	*	80	TCP	ALLOW
r_2	2	130.162.0.0/24	*		80	TCP	DENY
r_3	3	130.162.0.1/24	*	130.162.0.2/24	*	TCP	ALLOW
r_4	4	130.162.0.1/24	*	130.162.0.2/24	*	UDP	ALLOW
r_5	5	*	*	130.162.3.1	*	*	DENY
r_6	6	*	*	130.162.3.0/24	0-1024	TCP	ALLOW
r_7	7	*	*	130.162.3.0/24	*	*	DENY
...							
default	∞	*	*	*	*	*	DENY

FIGURE 1: Example of packet filter rule set (without anomalies)

rules themselves (intra-rule and inter-rules). These relations are then used to point out the anomalies and to reduce them to a minimum set. Moreover, in this work we propose a novel classification of firewall rule anomalies that extends and improves the previous works.

The remainder of the paper is structured as follows. Section II gives an overview of firewall operations, rules and anomalies, and the current state of the arts in this area. Section III presents the policy model, where we describe the proposed rule relations and the novel firewall anomaly taxonomy. Section IV describes the optimized anomaly resolution approach that we followed in this paper, and its implementation and validation. Finally, Section VI provides a brief conclusion of the paper.

II. BACKGROUND

Before the description of the proposed approach, in this section we briefly introduce the background on firewall operation and the policy-base managing.

A. FIREWALL

Firewalls are network security controls that regulate the traversal of packets by the definition of: (i) an ordered set of rules; (ii) a default action; (iii) a resolution strategy [15].

According to RFC-3198 [16], a *Rule* r is composed by a set of conditions C and one action a .

$$r = (C, a)$$

Each firewall condition, belonging to the C set, can be a single or a range of values and represents the possible values of the corresponding field in actual packets which match this rule. The Firewall actions can be *allow*, which forwards the packet, or *deny*, which discards the packet. Thus, the packet is allowed or denied by a specific rule if the packet header matches all the conditions of this rule. The *default action* is the action (i.e., allow or deny) to apply if the packet does not meet all the conditions of any rule.

Finally, the *resolution strategy* describes which rule's action should be applied if more than one rule matches the packet. Some example of resolution strategies are:

- *First Matching Rule* (FMR) selects the action from the first applicable rule in an ordered list;

- *Allow Takes Precedence* (ATP) where in case of contradicting actions that are simultaneously activated we enforce the Allow rule over the Deny one;
- *Deny Takes Precedence* (DTP) where in case of contradicting actions that are simultaneously activated we enforce the Deny rule over the Allow one (this is a restrictive strategy);
- *Most Specific Takes Precedence* (MSTP) where in case two conflicting rules are applied, the most specific rule is the one that takes precedence;
- *Least Specific Takes Precedence* (LSTP) where in case two conflicting rules are applied, the less specific rule is the one that takes precedence.

Without loss of generality, in this work, we consider the packet filter, the most common and used type of firewall, with deny as default action and FMR as resolution strategy. Specifically, in the packet filter condition fields are: source IP address, source port, destination IP address, destination port and protocol type (as show in the example in FIGURE 1).

$$r = (IPsrc, Psrc, IPdst, Pdst, Proto, Action)$$

B. POLICY-BASED MANAGEMENT

The application of policy-based management in network security has received increasing attention by the scientific community for many years, as reported in [17], [18]. The research on this topic mainly focuses on: *policy analysis*, *policy refinement* and *policy verification*.

Policy analysis checks the inconsistencies or sub-optimization in the specification of policy rule sets [11]. Policy analysis only concerns the policy specification and does not check if and how policies are enforced in the networks.

Policy refinement bridges the gap between specification and implementation. A policy refinement process, indeed, translates high-level requirements into low-level configurations (i.e., the policy rules) [19].

Finally, policy verification checks if a set of security properties/requirements are correctly enforced by low-level configurations of the security controls in the system. It is typically used to validate a hand-made security configuration [20].

	priority	IPsrc	Psrc	IPdst	Pdst	Proto	Action
r_1	1	130.162.0.1	*	130.162.0.2	80	TCP	ALLOW
r_2	2	130.162.1.3	*	130.162.2.2	*	UDP	ALLOW
r_3	3	130.162.0.1	*	130.162.0.2	80	TCP	DENY
r_4	4	130.162.1.0/24	*	130.162.2.0/24	*	*	ALLOW
r_5	5	130.162.1.0/24	*	130.162.2.0/24	80	*	ALLOW
r_6	6	130.162.3.0/24	*	130.162.0.0/24	*	*	DENY
r_7	7	130.162.3.1	*	130.162.0.1	80	TCP	ALLOW
r_8	8	130.162.1.1	*	130.162.2.1	22	TCP	ALLOW
r_9	9	130.162.1.4	*	130.162.2.5	0-1024	*	DENY
r_{10}	10	130.162.3.0/24	*	130.162.0.0/24	*	*	DENY
r_{11}	11	130.163.3.0/24	*	130.162.0.0/24	*	*	DENY
...							
default	∞	*	*	*	*	*	DENY

FIGURE 2: Example of packet filter rule set with anomalies

A common example of security property is network reachability, i.e., verify which kind of packets can travel from one node to another [21].

In this work we focus on the policy analysis. Several works can be found in the literature concerning policy analysis and the main contributions in this area mostly deal with *anomaly analysis* of firewall and VPN policies.

Anomaly analysis¹ looks for incorrect policy specifications that a network/security administrator may introduce. Anomaly analysis detects potential conflicts, errors and sub-optimizations affecting single or multiple policy sets [11].

One of the most influential works in this area is by Al-Shaer et al., which addresses the analysis of filtering configurations via First-Order Logic (FOL) formulas [4]. The authors classified and analysed both the local anomalies arising in a single firewall (intra-firewall anomaly) and the global ones taking into account several distributed filtering devices (inter-firewall anomaly).

Liu et al. focused on detecting and removing redundant filtering rules with data-structure named FDD (Firewall Decision Diagram) [22]. The authors distinguish upward redundant rules, which are rules that are never matched, and downward redundant rules, which are rules that are matched but enforce the same action as some lower priority rules.

Valenza et al. define and detect anomalies among different security functions (inter-function anomalies) [13]. The authors proposed a formal model able to detect several kinds of errors and anomalies that originate from correlations between configuration rules of different network functions. Their approach is able to cope with a wide array of different network functions, such as firewalls, NAT/NAPT devices, traffic monitors and encryption devices. In particular, they have presented three macro types of anomalies: blocked traffic, modified traffic and encrypted traffic.

Hu et al. [24], [14], propose FAME (Firewall Anomaly Management Environment) a visualization-based firewall policy manager. This tool identifies policy anomalies and

derives a possible resolution, by a rule-based segmentation technique and a grid-based representation. In our view, the automatic resolution the identify policy anomalies can potentially alter the original behaviours of the security administrators.

Basumatary et al. [25] propose a formal model for firewall anomaly detection. They represent firewall rules by a topological-temporal model and use a model checker to verify the firewall policy.

Krombi et al. [26], [27] propose a procedure that synthesizes an automaton that implements a given security policy. They use our automaton to verify completeness, detect anomalies, and discover functional discrepancies between several implementations of a security policy.

III. POLICY MODEL

In this section, we formally present the firewall rule relations enhancing the work described in [13], then we report the firewall policy anomalies extending the taxonomy presented in [4].

A. RULE RELATIONS

A correct model of rule relations is necessary for the analysis and detection of anomalies, derived from an erroneous specification. Our model, specifically, supports four types of relations between the condition fields (i.e., source IP address, destination IP address, source port, and destination port and protocol type), that are:

- **equivalence:** two condition fields f_x and f_y are equivalent if they have the same value (or range of values);

$$f_x = f_y$$

- **dominance:** a condition field f_x dominates another one f_y if it is a generalization of the second one.

$$f_x \succ f_y$$

For example, f_x is the source IP addresses 10.10.*.* and f_y is the source IP address 10.10.10.*, in this case f_x

¹In some works, anomaly analysis is called as either policy validation or conflict analysis.

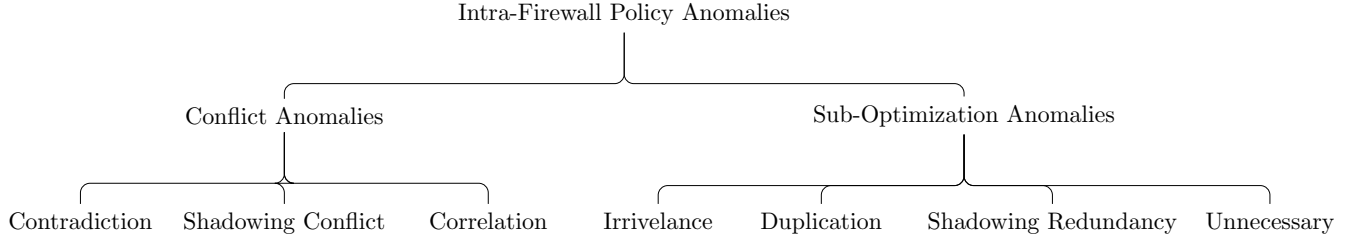


FIGURE 3: Taxonomy of Intra-Firewall Policy Anomalies

dominates f_y . The symbol $*$, called wildcards, allows to define a set or interval of values (e.g., 10.10.11.* stands for 10.10.11/24, whereas if $*$ refers to a port field it represents all the possible ports from 0 to 65535).

- **correlation**: two condition fields f_x and f_y are correlated if they share some values, but none of them includes (or dominates) the other one.

$$f_x \sim f_y$$

For example, if f_x and f_y are destination port and f_x value is 25-65, while f_y value is 40-75, then they are correlated because the range 40-65 is shared by both fields;

- **disjointness**: two condition fields f_x and f_y are disjoint if they do not share any value. On the other hand, if a network field is equivalent, correlated or dominates another, those fields are not-disjointed ($f_x \not\perp f_y$).

$$f_x \perp f_y$$

Having defined the relations among fields we proceed with the definition of relations among two condition sets, C_x and C_y . In particular, we define four possible relations among two conditions: *equivalence*, *dominance*, *correlation*, *disjointness*.

Please note that here we define the meaning of relations between conditions (e.g., C_x and C_y) using relations between corresponding condition fields (f_x^i and f_y^i).

Given two conditions C_x and C_y , only one of the following relations holds:

- **equivalence**: two conditions C_x and C_y are equivalent (or equal) if each condition field f_x^i in C_x is equivalent to the corresponding condition element f_y^i in C_y so that they exactly match the same packets (headers);

$$C_x \equiv C_y \Leftrightarrow f_x^i = f_y^i \forall i$$

For example, referring on the rules set in FIGURE 2, there is equivalence between the conditions of the rule r_1 and r_7 .

- **dominance**: a condition C_x dominates C_y ($C_x \succ C_y$) if it is a generalization of the latter. In other words, if the first condition set matches all the packet matched by the second, and some more (otherwise this would be an equivalence relation).

$$C_x \succ C_y \Leftrightarrow C_x \not\equiv C_y \wedge f_x^i \supseteq f_y^i \forall i$$

where $f_x \supseteq f_y$ stands for $f_x \succ f_y \vee f_x \equiv f_y$.

For example, the condition of rule r_4 dominates the conditions of the rule r_3 .

- **correlation**: two conditions C_x and C_y are correlated ($C_x \sim C_y$) if they match some common packets, but none of them includes (or dominates) the other one.

$$C_x \sim C_y \Leftrightarrow C_x \not\perp C_y \wedge C_x \not\supseteq C_y \wedge \forall i | f_x^i \not\perp f_y^i$$

where $C_x \not\perp C_y$ stands for $C_x \not\perp C_y \wedge C_x \neq C_y$. For example, the conditions of rule r_5 and r_9 are correlated.

- **disjointness**: two conditions are disjoint if they do not match any common packet.

$$C_x \perp C_y \Leftrightarrow \exists i | f_x^i \perp f_y^i$$

Please note that $C_x \not\perp C_y$ means that C_x and C_y are either equivalent, correlated or one dominates the other (i.e., \equiv, \succ, \sim).

For example, the conditions of rule r_1 and r_9 are disjoint.

Finally, the priority of a rule r is here represented with the function $\pi(r)$. Specifically, the function $\pi(r)$, returns the position of r in the ordered rule set. In this work we put at the top of the list the rules with the highest priority. In this way, between any two rules r_x and r_y it exists either the relation $\pi(r_x) > \pi(r_y)$ or the opposite $\pi(r_x) < \pi(r_y)$.

B. ANOMALIES

Policy anomalies typically occur when multiple authors defining the set of policy rules. Moreover, the modification or creation of a policy rule is a difficult task, because a new/updated policy can affect the behaviour of existing policies, defined by other people at different times. When firewalls contain a large number of rules, the risk of writing anomalies is significantly high [18].

In literature, there are two types of firewall policy anomaly: *intra-policy* and *inter-policy*².

An *intra-policy* anomaly is an anomaly among two rules in the same policy set (i.e., two rules of the same firewall), while an *inter-policy* anomaly is an anomaly among two rules in two different policy set (i.e., two rules of different firewalls).

In this work, we focus only on *intra-policy* anomalies where an optimized and effective firewall anomaly resolution is needed, as better described in Section IV.

²Note that in some works, the *intra-policy* anomalies are also called as *intra-firewall*, while the *inter-policy* as *inter-firewall*.

As shown in FIGURE 3, we distinguish two other main types of firewall policy anomaly, which are: *conflict* anomalies and *sub-optimization* anomalies.

A *sub-optimization* anomaly arises when redundant rules or other less efficient policy implementations are present.

A *conflict* anomaly arises when the effect of one rule is influenced or altered by another one, e.g. the actions of two rules (that are both satisfied simultaneously) contradict each other. Typically a conflict occurs when a set of policies rules (two or more) are simultaneously satisfied. This implies that the combined actions of the rules may produce different results depending on the order of execution of these actions. This is because the filtering procedure is performed by sequentially matching the packet against firewall rules until a match is found. Obviously, if the firewall rules are disjoint, the order of the rules does not influence the overall final behaviour.

Formally, given two rules $r_x = (C_x, a_x)$, $r_y = (C_y, a_y)$ with some relation (i.e., $C_x \not\subseteq C_y$), we have a conflict when $a_x \neq a_y$, otherwise we have a sub-optimization.

In our view, it is always possible to automatically solve the *sub-optimization* anomalies by applying some specific resolution strategy. *Conflict* anomalies, on the contrary, have to be manually solved by network administrators since it is not possible to define a single automatic resolution strategy that is valid in all the possible cases and that can solve all these anomalies, without potentially changing the behaviour of the related security policies.

In the following, we formally describe each intra-firewall anomaly and the possible action that a security/network administrator can perform in order to solve each anomaly.

1) Sub-optimization anomalies

As shown in FIGURE 3, we divide the sub-optimizations anomalies in four types: *Irrelevance*, *Duplication*, *Shadowing Redundancy*, *Unnecessary*.

Irrelevance

A policy rule r_x is irrelevant (i.e., $\mathcal{A}_{irr}(r_x)$) if it does not match any packet that might arrive to the firewall. This occurs, when either the source or the destination address of the rule, does not match with the subnet protected by the firewall.

$$\mathbb{A}_{irr} = \{r \in R | \mathcal{A}_{irr}(r)\}$$

Cancellation of an irrelevant policy rule does not alter the policy behaviour, while it will increase the system performance (as, in general, a large number of rules that are evaluated but never applied can hinder the performance of the filtering system).

For example, we can consider irrelevant the rule r_{11} in the FIGURE 2, because subnet 130.163.0.0/16 is not under the protection of the firewall where r_{11} is deployed.

Duplication Anomaly

A policy rule r_x duplicates rule r_y and vice versa if they specify the same action and match the same packets:

$$\begin{aligned} \mathbb{A}_{dupl} &= \{(r_x, r_y) \in R^2 | \mathcal{A}_{dupl}(r_x, r_y)\} \\ \mathcal{A}_{dupl}(r_x, r_y) &:= C_x \equiv C_y \wedge a_x = a_y \end{aligned}$$

In this case, the removal of the rule with the lowest priority π between r_x and r_y will not change the policy behaviour.

Referring on the example in FIGURE 2, there is a duplication anomaly between rules r_6 and r_{10} .

Shadowing Redundancy Anomaly

A policy rule r_y is shadowed by rule r_x if $\pi(r_x) > \pi(r_y)$ and all packets matched by r_y are also matched by r_x . In this case r_y will never be applied.

We specify the anomaly as a *Shadowing Redundancy* anomaly when r_x and r_y specify the same action:

$$\begin{aligned} \mathbb{A}_{shaRed} &= \{(r_x, r_y) \in R^2 | \mathcal{A}_{shaRed}(r_x, r_y)\} \\ \mathcal{A}_{shaRed}(r_x, r_y) &:= \pi(r_x) > \pi(r_y) \wedge C_x \supset C_y \wedge a_x = a_y \end{aligned}$$

In this case, the removal of r_y (i.e., the rule with the lower priority) is possible without changing the overall policy behaviour.

In the above example, we can find Shadowing Redundancy between rules r_4 and r_5 , r_4 and r_8 .

Unnecessary Anomaly

A policy rule r_x is redundant (i.e., unnecessary) with respect to rule r_y when: (i) r_x and r_y specify the same action, (ii) $\pi(r_y) < \pi(r_x)$ (r_x precedes r_y), (iii) all packets that are matched by r_x also matched by r_y , and (iv) it does not exist a rule $r_z \not\subseteq r_x$ with a priority between r_x and r_y ($\pi(r_y) < \pi(r_z) < \pi(r_x)$) and with opposite action.

$$\begin{aligned} \mathbb{A}_{unnec} &= \{(r_x, r_y) \in R^2 | \mathcal{A}_{unnec}(r_x, r_y)\} \\ \mathcal{A}_{unnec}(r_x, r_y) &:= \pi(r_x) > \pi(r_y) \wedge C_y \supset C_x \wedge a_x = a_y \wedge \\ &\quad \nexists r_z | \pi(r_x) < \pi(r_z) < \pi(r_y) \wedge C_z \not\subseteq C_x \wedge a_z \neq a_x \end{aligned}$$

In this case removal of r_x (i.e., the rule with higher priority) will not change the policy behaviour.

You can see an unnecessary anomaly between rule r_2 and r_4 .

2) Conflict Anomalies

We further classify conflict anomalies in three types: *Contradiction*, *Shadowing Conflict*, *Correlation*.

Contradiction Anomaly

Two policy rules r_x and r_y are in contradiction if they match the same packets but they specify different actions.

$$\begin{aligned} \mathbb{A}_{con} &= \{(r_x, r_y) \in R^2 | \mathcal{A}_{con}(r_x, r_y)\} \\ \mathcal{A}_{con}(r_x, r_y) &:= C_x \equiv C_y \wedge a_x \neq a_y \end{aligned}$$

An automatic removal of this anomaly is not possible, and an evaluation and action from the administrator is needed. Specifically, the administrator must decide which rule should be removed.

There is contradiction between the rule r_1 and r_3 .

Shadowing Conflict Anomaly

As mentioned before, a policy rule r_y is shadowed by rule r_x if $\pi(r_x) > \pi(r_y)$ and all packets matched by r_y are also matched by r_x . In this case r_y will never be applied.

We specify the anomaly as a *Shadowing Conflict* anomaly when the two rules specify different actions.

$$\mathbb{A}_{shaConf} = \{(r_x, r_y) \in R^2 \mid \mathcal{A}_{shaConf}(r_x, r_y)\}$$

$$\mathcal{A}_{shaConf}(r_x, r_y) := \pi(r_x) > \pi(r_y) \wedge C_x > C_y \wedge a_x \neq a_y$$

Also, in this case, the automatic resolution of this anomaly is not possible and the administrator must evaluate case by case. Specifically, in order to solve the anomaly, the administrator can decide to: (i) remove r_y ; or (ii) put r_y just before r_x ³.

You can find a shadowing conflict between rule r_6 and r_7 .

Correlation Anomaly Two policy rules are correlated, when they specify different actions and some packets that are matched by r_x also matched by r_y , but there are other packets that are either matched by r_x only or by r_y only.

$$\mathbb{A}_{corr} = \{(r_x, r_y) \in R^2 \mid \mathcal{A}_{corr}(r_x, r_y)\}$$

$$\mathcal{A}_{corr}(r_x, r_y) := C_x \sim C_y \wedge a_x \neq a_y$$

In order to solve a correlation anomaly, the administrator can decide to: (i) leave everything as it is; or (ii) re-write r_y and r_x . There are correlations between rules r_4 and r_9 , r_5 and r_9 .

It is important to note that *Duplication*, *Contradiction* and *Correlation Anomalies* are symmetric relations.

$$\mathcal{A}_{dupl}(r_x, r_y) \leftrightarrow \mathcal{A}_{dupl}(r_y, r_x)$$

$$\mathcal{A}_{con}(r_x, r_y) \leftrightarrow \mathcal{A}_{con}(r_y, r_x)$$

$$\mathcal{A}_{corr}(r_x, r_y) \leftrightarrow \mathcal{A}_{corr}(r_y, r_x)$$

Finally, the TABLE 1 summarizes the actions that an administrator can do in order to solve each intra-firewall anomaly. It is important to highlight that, in our view, except for the irrelevance anomalies, the other types of anomalies are not errors. In other words, each rule is individually correct and well written, but it is the interaction with other rules that may create anomalies.

$\mathcal{A}_{dupl}(r_x, r_y)$ • remove r_x • remove r_y	$\mathcal{A}_{shaRed}(r_x, r_y)$ • remove r_y	$\mathcal{A}_{unn}(r_x, r_y)$ • remove r_x	$\mathcal{A}_{irr}(r_x)$ • remove r_x
$\mathcal{A}_{con}(r_x, r_y)$ • remove r_y • remove r_x	$\mathcal{A}_{shaConf}(r_x, r_y)$ • remove r_y • put r_y just before r_x	$\mathcal{A}_{cor}(r_x, r_y)$ • leave everything as it is • re-write r_y and r_x	

TABLE 1: Summary of fixing actions for each anomaly

IV. OPTIMIZED RESOLUTION

In this section we present the actual optimized resolution strategy, able to minimize the number of anomalies to be solved by the administrator. Specifically, our goal is to reduce the number of *conflict* anomalies that should be manually solved by administrators.

³In this case, each rule after r_x will shift of one position.

The evaluation of all the possible relations among a firewall rule set, and thus the identification of their anomalies, is a complex task that, given their formal definition presented before, can however be straightforwardly automatized in a software tool. On the other hand, the subsequent process of anomaly resolution is more difficult. As described in Section II, in literature, some approaches that propose to resolve all the anomalies in a completely automatic way do exist [14]. However, this implies that the administrator has little to no control over the resolution and particularly ambiguous and critical cases could be overlooked. Here we prefer a semi-automatic approach, that keeps the administrator always in control when possible ambiguities arise. More specifically, we propose a strategy to be followed that (i) avoids anomalies that are actually not relevant, (ii) does not introduce new anomalies and that (iii) quickly converges to a stable solution, without having to repeat the process multiple times.

Given the types and characteristics of the defined anomalies and the possible relations among the involved rules, it is possible to describe an optimized resolution strategy, that satisfies the requirements, as follows:

- 1) Consider firstly all the *Irrelevance* anomalies \mathbb{A}_{irr} . Clearly, the involved rules can be removed as they cannot affect the overall firewall behaviour. As a direct consequence, all anomalies (of different types) that include these same rules can be removed as well, reducing the set of anomalies to be considered;

Remove $\forall r \in \mathbb{A}_{irr}$:

$$\begin{cases} \mathbb{A}_\alpha = \mathbb{A}_\alpha \setminus \{(r_1, r_2) \mid r_1 = r \vee r_2 = r\}, \\ \alpha \in \{dup, shaRed, con, shaConf, cor, unn\} \end{cases}$$

- 2) Then, consider then all the *Duplication* anomalies \mathbb{A}_{dupl} . Each one of these anomalies involves two rules r_x and r_y , where r_y has a lower priority with respect to r_x (that is $\pi(r_x) > \pi(r_y)$) and where the specified actions are the same. In this case, r_y can always be safely removed, without affecting the firewall behaviour. Again, all the other anomalies that involve the removed rules, have to be cleared;

Remove $\forall r_y \mid (r_x, r_y) \in \mathbb{A}_{dupl}$:

$$\begin{cases} \mathbb{A}_\alpha = \mathbb{A}_\alpha \setminus \{(r_1, r_2) \mid r_1 = r_y \vee r_2 = r_y\}, \\ \alpha \in \{shaRed, con, shaConf, cor, unn\} \end{cases}$$

- 3) Next consider the *Shadowing Redundancy* anomalies \mathbb{A}_{shaRed} , where, again, the actions of the involved rules are the same. Among all the anomalies of this type, we must consider firstly the anomalies rules where the corresponding r_x has the highest priority. In fact, a shadowing rule can actually completely shadow pair of rules that are involved in other anomalies, thus “shadowing” the other anomalies themselves. For the same reason, among *Shadowing Redundancy* anomalies with the same priority $\pi(r_x)$, the first to be considered are

the ones with the highest priority $\pi(r_y)$. For each considered anomaly, it is then possible to remove the rule r_y and propagate this removal by clearing the remaining anomaly set;

$$\begin{aligned} &\text{Remove } \forall r_y | (r_x, r_y) \in \mathbb{A}_{shaRed} : \\ &\left\{ \begin{array}{l} \mathbb{A}_\alpha = \mathbb{A}_\alpha \setminus \{(r_1, r_2) | r_1 = r_y \vee r_2 = r_y\}, \\ \alpha \in \{con, shaConf, cor, unn\} \end{array} \right\} \end{aligned}$$

- 4) After this, we consider the *Contradiction* anomalies \mathbb{A}_{con} , where the rule conditions match exactly the same packets but with opposite actions. This case is similar to the *Duplication* one but does require an explicit evaluation from the administrator. He/she can decide either to remove one between r_x and r_y . Then the procedure continues in the usual way, by clearing all the affected anomalies.

$$\begin{aligned} &\text{Remove } \forall r_y | (r_x, r_y) \in \mathbb{A}_{con} : \\ &\left\{ \begin{array}{l} \mathbb{A}_\alpha = \mathbb{A}_\alpha \setminus \{(r_1, r_2) | r_1 = r_x \vee r_2 = r_x\}, \\ \alpha \in \{con, shaConf, cor, unn\} \end{array} \right\} \\ &\text{Remove } \forall r_y | (r_x, r_y) \in \mathbb{A}_{con} : \\ &\left\{ \begin{array}{l} \mathbb{A}_\alpha = \mathbb{A}_\alpha \setminus \{(r_1, r_2) | r_1 = r_y \vee r_2 = r_y\}, \\ \alpha \in \{con, shaConf, cor, unn\} \end{array} \right\} \end{aligned}$$

- 5) Next we consider every *Shadowing Conflict* anomaly $\mathbb{A}_{shaConf}$, where r_x is shadowing r_y and has an opposite action. Also in this case, the administrator has to evaluate the specific situation and decide how to act. Two possible decisions can be made: (i) remove r_y , (ii) move r_y just before r_x (meaning $\pi(r_y) > \pi(r_x)$). When (i) is applied the resolution process proceeds as usual, removing all the anomalies involving r_y . When (ii) is preferred, instead, the best course of actions is to choose firstly the anomaly with the highest priority (that is the highest $\pi(r_x)$) and move the corresponding r_y . Moving the rule r_y to a higher priority place before r_x means that the administrator has decided that, for all the packets matching the C_y condition, the firewall must apply the a_y action. This decision can be propagated and applied to solve other anomalies that involves r_y . For example, let's consider a rule $r_z = (C_z, a_x)$ for which $\mathcal{A}_{corr}(r_y, r_z)$ holds ($(r_y, r_z) \in \mathbb{A}_{corr}$). If $\pi(r_z) < \pi(r_x)$ we can confirm the decision of the administrator and apply it also for those packets p that match both C_y and C_z . In fact, these packets are a subset of the packets that match C_y , and the administrator has already established the correct action to apply for C_y . For this reason, the correlation between r_y and r_z is not an anomaly anymore and can be removed. The same

reasoning is valid if $\mathcal{A}_{shaConf}(r_y, r_z)$ holds.

$$\begin{aligned} &\text{Remove } \forall r_y | (r_x, r_y) \in \mathbb{A}_{shaConf} : \\ &\left\{ \begin{array}{l} \mathbb{A}_\alpha = \mathbb{A}_\alpha \setminus \{(r_1, r_2) | r_1 = r_x \vee r_2 = r_x\}, \\ \alpha \in \{shaConf, cor, unn\} \end{array} \right\} \\ &\text{Move } \forall r_y \text{ just before } r_x | (r_x, r_y) \in \mathbb{A}_{shaConf} : \\ &\left\{ \begin{array}{l} \mathbb{A}_\alpha = \mathbb{A}_\alpha \setminus \{(r_1, r_2) | \pi(r_z) < \pi(r_x)\}, \\ \alpha \in \{shaConf, cor\} \end{array} \right\} \end{aligned}$$

- 6) *Correlation* anomalies are considered at this point. This kind of anomaly has to be solved by the administrator, who has two options: either to (i) leave everything as it is (*accept*) or (ii) re-write r_x and r_y . In this latter case, the anomaly detection and resolution process should be restarted in order to detect and solve the new anomalies potentially introduced by the administrator. In any case, the process can continue as usual, by removing all the other anomalies that are connected to the removed rule.
- 7) Finally, the resulting set of rules has to be analysed again looking for *Unnecessary* anomalies. It is worth noting, in fact, that at this point, after all the previous steps, the only kind of anomaly that can still be present is the *Unnecessary* one. Moreover, some new (*Unnecessary*) anomalies could have been introduced with respect to the initial set of rules, due to the shifts among other rules. These anomalies are dealt with in this last step as they can be easily solved by removing the r_x rule (that is the rule with highest priority that is completely dominated by r_y).

At the end of this process, the initial set of rules have been reduced and all the anomalies solved.

V. EVALUATION

In this section, we present the validation and implementation of the proposed approach.

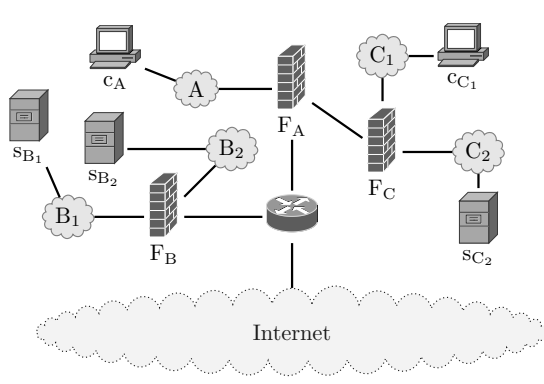
A. VALIDATION

In order to validate the usefulness of our work, we had applied our optimized firewall anomaly resolution in a realistic scenario. Due to space limit and readability, we propose a network system which is small, but at the same time is able to show and stress the main aspects of the solution.

As shown in FIGURE 4, we have a network composed of three subnets A , B and C . Each subnet is protected by a specific firewall F_A , F_B and F_C . Moreover, we know some IP addresses, related to specific clients and servers of the network (i.e., $c_A, c_{C_1}, s_{B_1}, s_{B_2}, s_{C_2}$).

In this network scenario, we define six high-level policies:

- The subnet A is allowed to reach the subnet B ;
- The subnet C_1 and C_2 are not allowed to reach B ;
- The network nodes inside the subnet B are allowed to talk one to each other;
- Only s_{B_2} and c_A are allowed to talk with s_{B_1}
- Only s_{C_2} and s_{B_1} are allowed to talk with s_{B_2}



LEGEND				
router	firewall	filt. zone	client	server
VALUES				
A: 10.1.0.0/24, c_a : 10.1.0.7				
B_1 : 10.2.0.0/24, s_{B1} : 10.2.0.5:80				
B_2 : 10.2.1.0/24, s_{B2} : 10.2.1.5:8080				
C_1 : 10.3.0.0/24, c_{C1} : 10.3.0.7				
C_2 : 10.3.1.0/24, s_{C2} : 10.3.1.5:80 10.3.1.5:80,8080				

FIGURE 4: The reference network

Wrong configuration								Detected Anomalies	
	priority	IPsrc	Psrc	IPdst	Pdst	Proto	Action	Irrelevance:	Shad. Conf.:
r_1	1	10.1.0.0/24	*	*	*	*	DENY	(1) $\mathcal{A}_{irr}(r_3)$	(16) $\mathcal{A}_{shaConf}(r_1, r_2)$
r_2	2	10.1.0.0/24	*	*	*	TCP	ALLOW	(2) $\mathcal{A}_{irr}(r_4)$	(17) $\mathcal{A}_{shaConf}(r_1, r_5)$
r_3	3	10.1.0.0/24	*	10.3.0.0/24	*	TCP	DENY		(16) $\mathcal{A}_{shaConf}(r_2, r_3)$
r_4	4	10.1.0.0/24	*	10.3.1.0/24	*	TCP	DENY		(18) $\mathcal{A}_{shaConf}(r_2, r_4)$
r_5	5	10.1.0.7	*	10.2.0.5	80	TCP	ALLOW	(3) $\mathcal{A}_{shaRed}(r_1, r_3)$	(19) $\mathcal{A}_{shaConf}(r_7, r_{17})$
r_6	6	10.2.0.5	80	10.1.0.7	*	TCP	ALLOW	(4) $\mathcal{A}_{shaRed}(r_1, r_4)$	(20) $\mathcal{A}_{shaConf}(r_8, r_{18})$
r_7	7	10.2.0.5	*	*	*	*	DENY	(5) $\mathcal{A}_{shaRed}(r_2, r_5)$	(21) $\mathcal{A}_{shaConf}(r_9, r_{12})$
r_8	8	*	*	10.2.0.5	*	*	DENY		(22) $\mathcal{A}_{shaConf}(r_9, r_{18})$
r_9	9	10.2.1.5	*	*	*	*	DENY		(23) $\mathcal{A}_{shaConf}(r_{10}, r_{11})$
r_{10}	10	*	*	10.2.1.5	*	*	DENY		(6) $\mathcal{A}_{corr}(r_7, r_{19})$
r_{11}	11	10.3.1.5	80	10.2.1.5	8080	TCP	ALLOW	(7) $\mathcal{A}_{corr}(r_8, r_{20})$	(24) $\mathcal{A}_{shaConf}(r_{10}, r_{17})$
r_{12}	12	10.2.1.5	8080	10.3.1.5	80	TCP	ALLOW	(8) $\mathcal{A}_{corr}(r_9, r_{20})$	(25) $\mathcal{A}_{shaConf}(r_{13}, r_{17})$
r_{13}	13	10.2.0.0/24	*	*	*	*	DENY	(9) $\mathcal{A}_{corr}(r_{10}, r_{19})$	(26) $\mathcal{A}_{shaConf}(r_{13}, r_{19})$
r_{14}	14	*	*	10.2.0.0/24	*	*	DENY		(27) $\mathcal{A}_{shaConf}(r_{14}, r_{18})$
r_{15}	15	10.2.1.0/24	*	*	*	*	DENY		(28) $\mathcal{A}_{shaConf}(r_{14}, r_{20})$
r_{16}	16	*	*	10.2.1.0/24	*	*	DENY		(29) $\mathcal{A}_{shaConf}(r_{15}, r_{18})$
r_{17}	17	10.2.0.5	80	10.2.1.5	8080	TCP	ALLOW		(30) $\mathcal{A}_{shaConf}(r_{15}, r_{20})$
r_{18}	18	10.2.1.5	8080	10.2.0.5	80	TCP	ALLOW		(31) $\mathcal{A}_{shaConf}(r_{16}, r_{17})$
r_{19}	19	10.2.0.0/24	*	10.2.1.0/24	*	*	ALLOW		(32) $\mathcal{A}_{shaConf}(r_{16}, r_{19})$
r_{20}	20	10.2.1.0/24	*	10.2.0.0/24	*	*	ALLOW		
r_{21}	21	10.3.0.0/16	*	10.2.0.0/16	*	*	DENY		
r_{22}	22	10.2.0.0/16	*	10.3.0.0/16	*	*	DENY		
default	∞	*	*	*	*	*	DENY		

FIGURE 5: The F_B configuration and its intra-firewall anomalies

Resolved Anomalies		Novel configuration							
		priority	IPsrc	Psrc	IPdst	Pdst	Proto	Action	
Irrelevance:		r_2	1	10.1.0.0/24	*	*	TCP	ALLOW	
(1) $\mathcal{A}_{irr}(r_3)$		r_6	2	10.2.0.5	80	10.1.0.7	TCP	ALLOW	
(2) $\mathcal{A}_{irr}(r_4)$		r_{11}	3	10.3.1.5	80	10.2.1.5	TCP	ALLOW	
Shad. Red.:		r_{12}	4	10.2.1.5	8080	10.3.1.5	TCP	ALLOW	
(5) $\mathcal{A}_{shaRed}(r_2, r_5)$		r_{17}	5	10.2.0.5	80	10.2.1.5	TCP	ALLOW	
Shad. Conf.:		r_{18}	6	10.2.1.5	8080	10.2.0.5	TCP	ALLOW	
(16) $\mathcal{A}_{shaConf}(r_1, r_2)$		r_7	7	10.2.0.5	*	*	*	DENY	
(19) $\mathcal{A}_{shaConf}(r_7, r_{17})$		r_8	8	*	*	10.2.0.5	*	DENY	
(20) $\mathcal{A}_{shaConf}(r_8, r_{18})$		r_9	9	10.2.1.5	*	*	*	DENY	
(21) $\mathcal{A}_{shaConf}(r_9, r_{12})$		r_{10}	10	*	*	10.2.1.5	*	DENY	
(23) $\mathcal{A}_{shaConf}(r_{10}, r_{11})$		r_{19}	11	10.2.0.0/24	*	10.2.1.0/24	*	ALLOW	
(26) $\mathcal{A}_{shaConf}(r_{13}, r_{19})$		r_{20}	12	10.2.1.0/24	*	10.2.0.0/24	*	ALLOW	
(28) $\mathcal{A}_{shaConf}(r_{14}, r_{20})$		default	∞	*	*	*	*	DENY	
(30) $\mathcal{A}_{shaConf}(r_{15}, r_{20})$									

FIGURE 6: The resolved anomalies and the novel F_B configuration

- Only a subset of network nodes (i.e., specified in other policies) is allowed to reach the subnet B .

In this example, the network security administrator has followed these high-level policies to implement the configurations of all the firewalls, including the specific configuration for firewall F_B , shown in FIGURE 5. However, this initial configuration has some flaws. Specifically, there are 32 anomalies: 2 Irrelevance, 3 Shadowing Redundancy, 18 Shadowing Conflict, 4 Correlation and 6 Unnecessary. These anomalies are listed and numbered in FIGURE 5,

In this scenario we applied the proposed algorithm described in the previous Section, following these steps:

- 1) we solved the Irrelevance anomaly (1) by removing rule r_3 . Consequently anomalies (3) and (16) disappear;
- 2) we solved the Irrelevance anomaly (2) by removing rule r_4 . Consequently anomalies (4) and (18) disappear;
- 3) we solved Shadowing Redundancy anomaly (5) by removing rule r_5 . Consequently anomaly (5) disappears;
- 4) we solved the Shadowing Conflict anomaly (16) by moving rule r_2 before r_1 ;
- 5) we solved the Shadowing Conflict anomaly (19) by moving rule r_{17} just before r_7 . Consequently anomalies (12), (24), (25) and (31) disappear;
- 6) we solved the Shadowing Conflict anomaly (20) by moving rule r_{18} just before r_8 . Consequently anomalies (13), (22), (27) and (29) disappear;
- 7) we solved the Shadowing Conflict anomaly (21) by moving rule r_{12} just before r_9 ;
- 8) we solved the Shadowing Conflict anomaly (23) by moving rule r_{11} just before r_{10} ;
- 9) we solved the Shadowing Conflict anomaly (26) by moving rule r_{19} just before r_{13} . Consequently anomalies (10) and (32) disappear;
- 10) we solved the Shadowing Conflict anomaly (28) by moving rule r_{20} just before r_{14} . Consequently anomalies (11) and (30) disappear;
- 11) we marked the Correlation anomalies (6), (7), (8), (9), as solved, assuming the administrator accepts them;
- 12) we solved the Unnecessary anomalies (14) and (15) respectively by removing rules r_{21} and r_{22} ;
- 13) finally, we solved the newly introduced Unnecessary anomalies (33), (34), (35), (36) and (37) respectively by removing rules r_1 , r_{13} , r_{14} , r_{15} and r_{16} .

As shown in FIGURE 6, using our optimized resolution, we reduced the number of rules to 12 by solving only 22 anomalies, 16 of which are coming from the original flawed configuration and 5 are new Unnecessary anomalies introduced by the resolution process. It is worth remarking that this type of anomaly is easily solved by removing one rule, thus reducing the set of rules without requiring administrator's actions.

It is important to note that the number of anomalies that automatically disappear depends on the specific scenario. However, it is evident that the proposed approach significantly reduces the administrator's effort.

B. IMPLEMENTATION

We implemented the proposed methodology and techniques in a prototype software tool. This prototype has been written in Java for portability and is composed by two modules.

The first module reads the description of a network topology and the configuration of the included firewalls. Then, it performs a first analysis to collect all the anomalies among firewall rules, as defined in previous sections.

The second module evaluates the complete set of anomalies and finds, if any, the minimum set of anomalies to solve and the related optimal resolution strategy to propose to the administrator. The strategy computed by this module can be adapted to the choice of the administrator by introducing custom priorities among different rules.

We tested this implementation on the example presented in previous sections and we built several other test cases based on larger synthetic networks. In each test we randomly changed the order of the rules to generate different initial anomaly sets.

These tests were performed to assess the feasibility of the methodology, even in a prototype version of the tool, in its two main aspects: to find the anomalies and to suggest the optimized resolution strategy.

Specifically, we conducted our experiments on an Intel Core i7 3.40Ghz machine with 16GB of RAM. As preliminary results, the conducted tests confirmed the feasibility of the approach applied to realistic cases. In all the experiments the number of total anomalies to be considered has been reduced with respect to the initial set, confirming the usefulness of the approach.

VI. CONCLUSION

In this work, we present a formal approach to optimize the firewall anomaly resolution. Specifically, our proposed approach is able to reduce the set of anomalies, that an administrator should solve in order to remove all the anomalies among firewalls rules. Moreover we propose a novel rule relations model and intra-firewall anomaly classification. Finally, the performance of the solution was evaluated in realistic network scenarios and by a Java-based prototype of the presented approach.

As possible future work, we plan to extend the expressiveness and capabilities of our model to make it able to solve problems relative to the attribute-based access control, strictly related to firewall behaviours, and to perform some empirical study with network security administrator, in order to improve the usability of our tool.

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of the same critical systems.

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